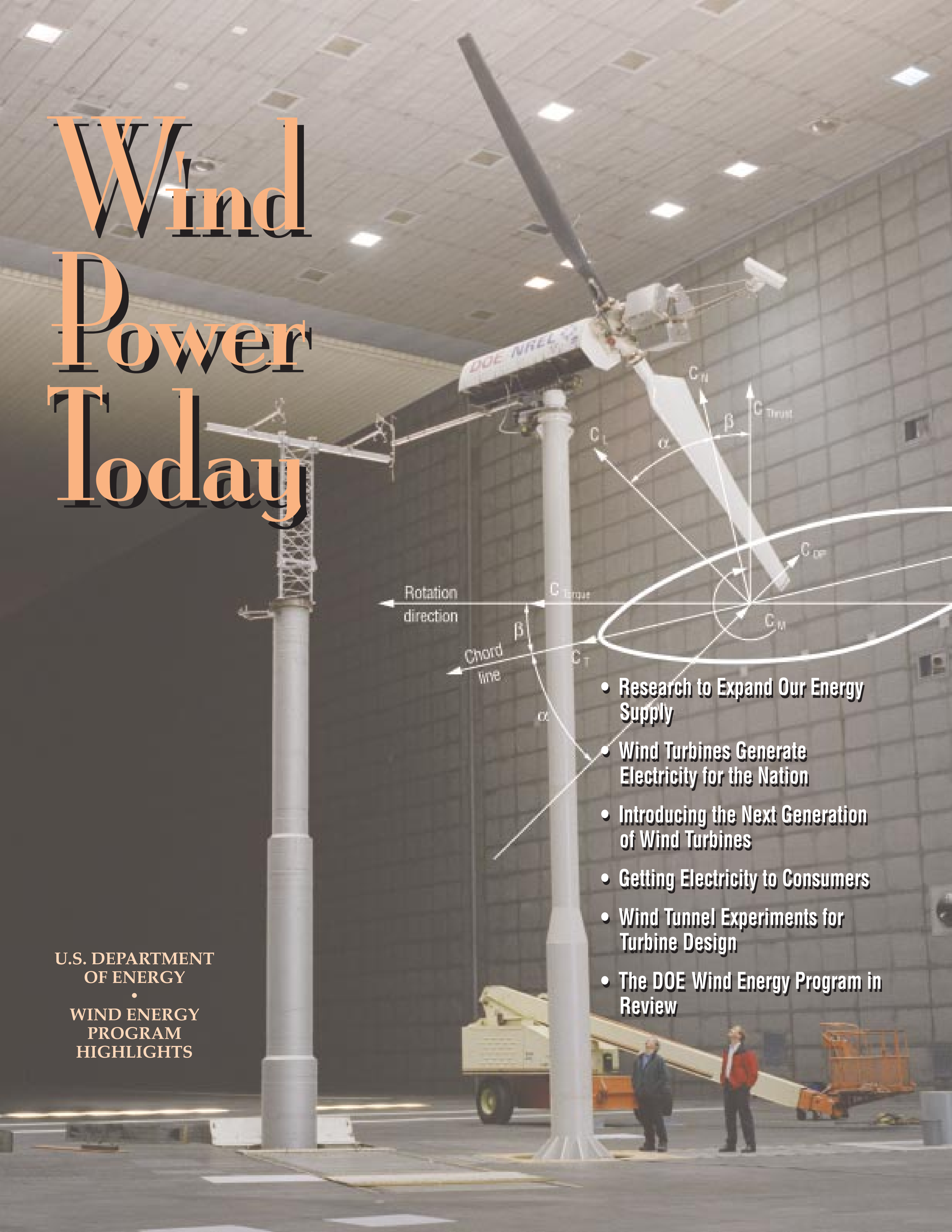
Wind Power Today



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U.S. DEPARTMENT OF ENERGY
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WIND ENERGY PROGRAM HIGHLIGHTS

2000: THE YEAR IN REVIEW

Cover photo: ***Wind tunnel experiments at the NASA Ames Research Center in FY 2000 generated data that will help make aerodynamic models that more accurately predict the stresses imposed on wind turbines during operation.***

About "Wind Power Today"

Wind power is expanding the electrical generation capacity of the United States at a time when the capacity of conventional electrical generation is taxed to the limit. In addition, wind power has the potential to contribute a great deal more. Through its Wind Energy Program, the U.S. Department of Energy is working with the wind industry and universities on advanced components to make future wind-generating systems cost effective in broad regions of the United States, while increasing the amount of electricity a single machine produces. Research conducted in wind tunnels and in the field is expanding our understanding of the aerodynamic forces on wind turbines so that design models can be improved. Work is also under way to help ensure that the electrical generation, transmission, and distribution systems can handle the electricity wind farms will generate in the years to come.

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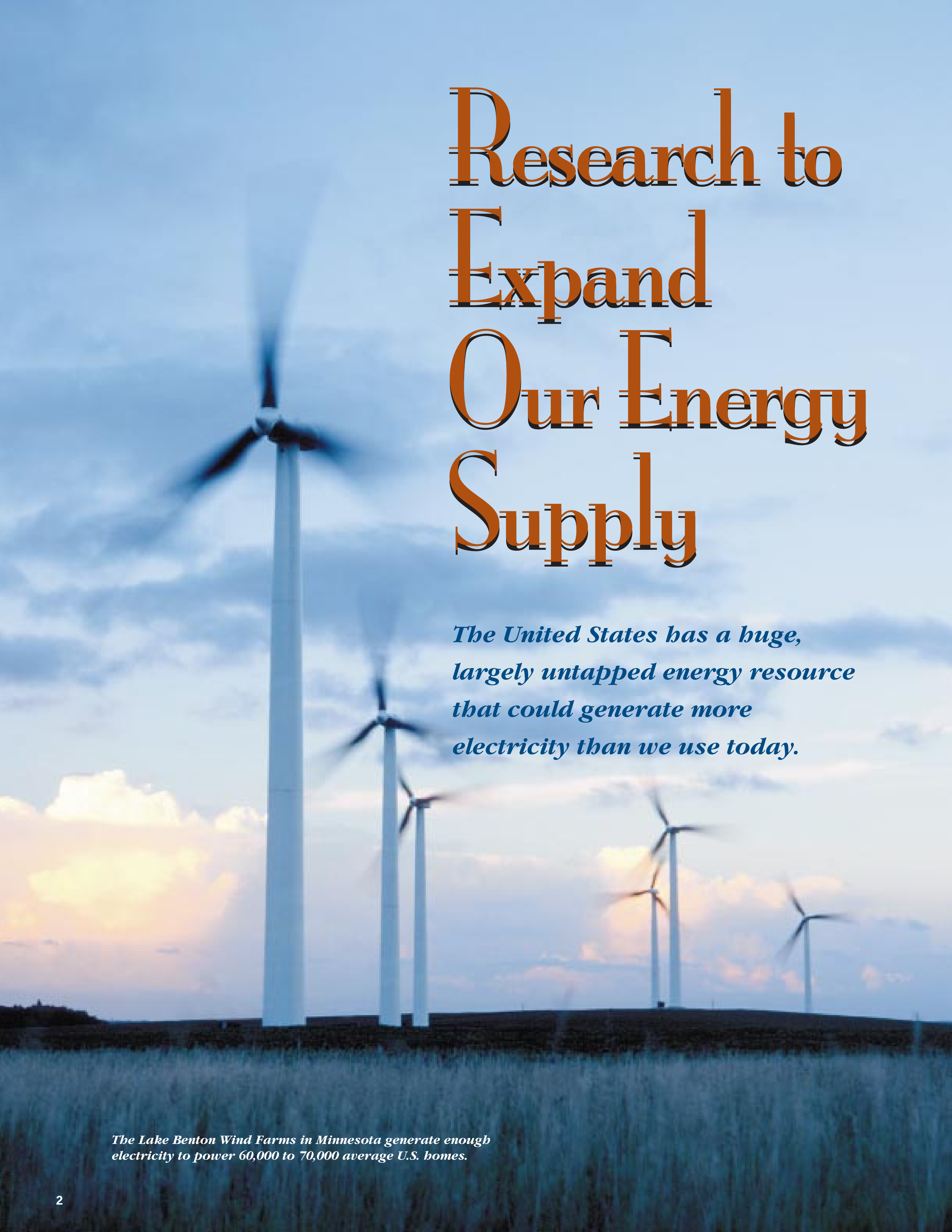
Research to Expand Our Energy Supply

The United States has a huge, largely untapped energy resource that could generate more electricity than we use today.



The Lake Benton Wind Farms in Minnesota generate enough electricity to power 60,000 to 70,000 average U.S. homes.

FROM WEST VIRGINIA TO PENNSYLVANIA, FROM ALASKA TO NEW JERSEY, PEOPLE ARE amazed to hear of the abundant energy available in the winds that blow across our nation. More than 1,200 gigawatts (more than 1 million megawatts [MW]) of wind power potential are available at sites across the country, according to analysts. This is much more electricity than we use today. In 2000, our nation's generating capacity from all sources was only 775 gigawatts.

Our challenge is to perfect the technology required to harvest this vast resource and reliably deliver it to consumers at a competitive price as a viable part of our nation's energy mix. For more than two decades, the U.S. Department of Energy (DOE), through its Wind Energy Program, has sponsored research, testing, and development activities that have helped reduce the cost of wind-generated electricity. Since 1980, the cost of electricity from wind systems at good wind sites without subsidies[1] has been reduced from $0.35/kilowatt-hour (kWh) to between $0.04 and $0.06/kWh today.

Although costs have decreased significantly, researchers believe that further improvements could reduce costs an additional 30% to 50%. The Wind Program's goal is to advance the science and technology so that utility-scale, grid-connected wind power systems can produce electricity for $0.03/kWh at excellent wind sites by 2004, and for $0.03–$0.04/kWh at more moderate wind sites by 2007–2015.

REDUCING LOADS TO LOWER COSTS

Working alone, it would take industry a long time to reach these ambitious cost goals. For example, wind turbine manufacturers have been developing new designs while supplying viable products to the current market. To remain competitive, they innovate slowly on an incremental scale using design changes that pose little risk. To cut the cost of energy in half will demand significant innovations that push the limits of both our scientific understanding and our manufacturing techniques. Because these innovations may not bear fruit immediately, DOE encourages the long-term commitment of funds and research staff through its competitively selected research partnerships with industry. Such partnerships are crucial to developing the technologies that will ultimately expand our domestic renewable energy supply.

The U.S. Department of Energy's Wind Energy Program sponsors research, testing, and development activities to help reduce the cost of wind-generated electricity.

Large cost reductions are possible, researchers believe, because current wind turbine designs take a very conservative approach to dealing with loads, and this conservative approach adds to the cost of the turbines. Loads or stresses on a wind turbine come from forces in the wind that interact with all the components of the system. Today's turbines are overdesigned to compensate for the fact that design tools do not accurately predict the loads on all components. This large margin of error has two main

[1] These calculations assume that commercial project financing costs around 7.5% annual return on debt, and about 13% or less return on equity—reasonable rates for an established power generating company.

Large cost reductions are possible, researchers believe, because current wind turbine designs take a very conservative approach to dealing with loads.

consequences. First, it reduces the amount of energy that is actually captured from the wind, and second, it increases the cost of hardware by requiring the use of heavier and stronger materials than might otherwise be necessary. The refinement of structural dynamics codes allows better prediction of loads leading to increased confidence and lower safety factors.

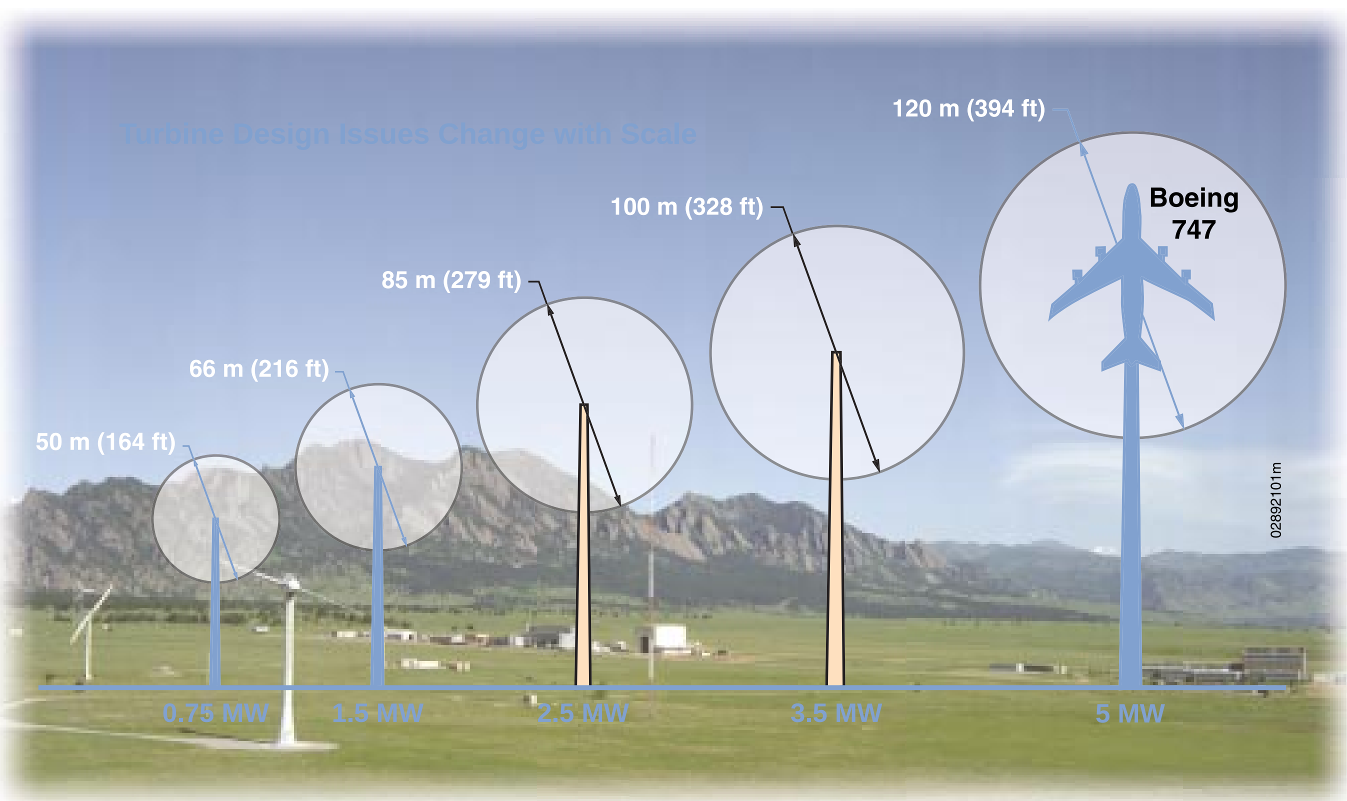
Many new designs have been proposed for less costly ways of dealing with loads on wind turbines. In addition, new materials and electrical devices, developed for other industries, present new possibilities for implementing old ideas for wind turbine design. The Wind Program's research partnerships aim to reduce the risk of incorporating such innovations into prototype wind turbine components and systems. The prototypes will then provide information to aid in the design of proprietary products that will be deployed to expand our domestic electricity production.

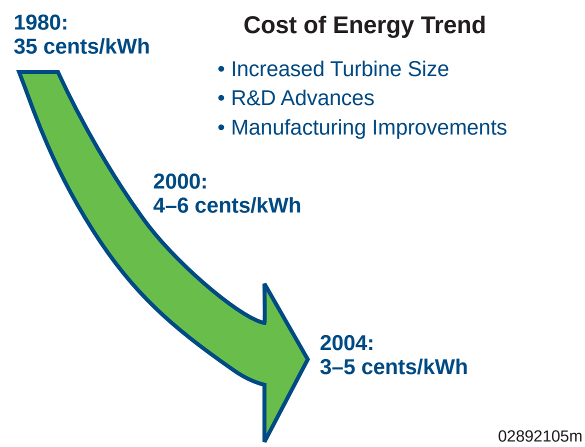
WIND PARTNERSHIPS FOR ADVANCED COMPONENT TECHNOLOGIES (WINDPACT)

Wind turbine manufacturers have reduced the cost of wind energy by improving manufacturing techniques, taking advantage of the latest engineering tools, applying new concepts to existing designs, and increasing turbine size. However, significant innovations are required to achieve the cost goals that will make electricity from wind turbines competitive with that from other forms of generation. Such innovations are considered "high risk" and will require the wind industry, with significant support from the DOE and its laboratories, to leap beyond the traditional, incremental improvements.

The goal of WindPACT is to support the research necessary for industry to continue development of products that reduce the cost of energy from wind turbines and to determine the best size of advanced utility-scale turbines in the United States. To reach the WindPACT goal, research partnerships are exploring design concepts too risky for today's industry to explore while meeting the demands of the current energy market. These advanced designs for individual components hold the potential for reducing loads, improving performance and reliability, and reducing costs.

One approach used to reduce the cost of energy is to make wind turbines larger and develop new technology required for increased size. In 1997, the





Research will address large turbine design issues to reduce the cost of energy.

average turbines installed were rated to generate between 600 and 750 kilowatts (kW)—enough electricity to power approximately 250 average homes. In 2000, manufacturers were beginning to install machines rated from 1 to 2 MW (or 1,000 to 2,000 kW), and many manufacturers are currently designing turbines with even higher ratings. These larger machines are generally targeted for offshore installations in shallow waters of the European coast. This trend to develop larger turbines is driven by economics. Turbines can generate more electricity if the length of the rotor blades is increased. This in turn requires a taller tower and a larger generator. In short, everything is scaled up to generate more electricity from a single machine. For offshore turbines, a cost increase is acceptable because of the high cost of the platform and electrical power cable to shore. The minimum cost of energy for the offshore system is obtained by installing the largest turbine possible within the design limitations of the platform and turbines.

It is important to identify and understand the primary design drivers of increasing size and determine where the increase in scale will be optimal. Size increases challenge designers who have not yet dealt with the issues larger components present. The two major phases of the WindPACT project are designed to increase the efficiency of wind turbines and lower the cost of the electricity they produce. The first phase is a study of scaling and design issues to identify technologies or areas of research that hold the greatest promise for decreasing cost and improving performance of wind turbines. After the scaling and design studies are completed, the second phase will select key technologies for more detailed design, fabrication, and testing by industry subcontractors.

There are many reasons why scaling up to larger turbines might reduce the cost of electricity to the customer. Depending on the layout of the wind farm, larger turbines can extract

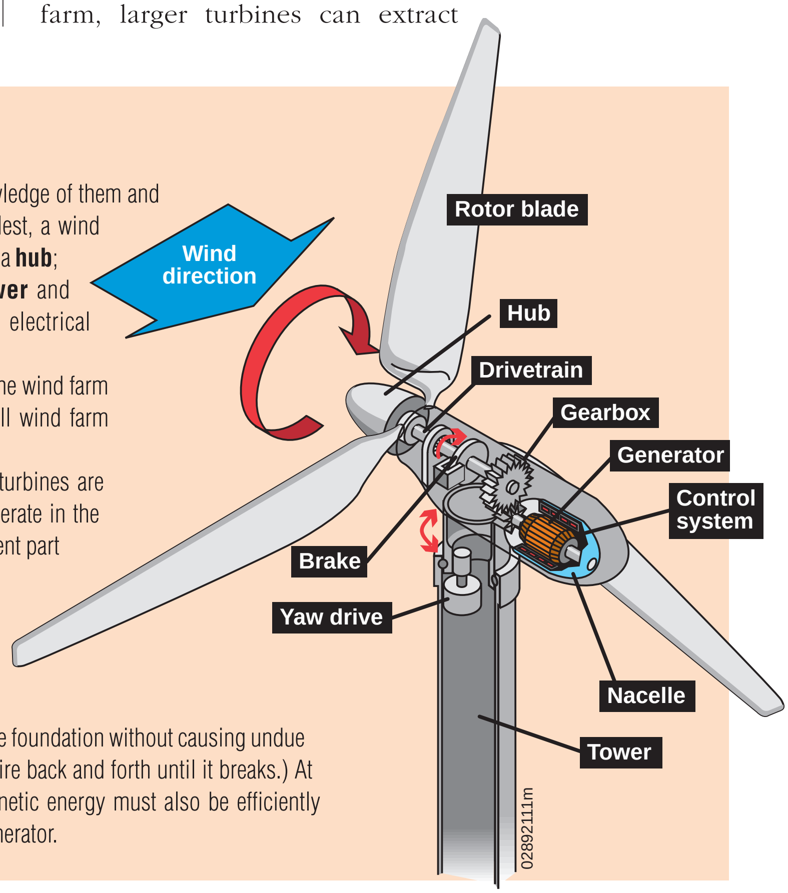
The Parts of a Wind Turbine

Many of the principles used in wind energy are centuries old, yet our knowledge of them and how we apply them has changed dramatically in recent decades. At its simplest, a wind turbine consists of a **rotor** that has aerodynamically shaped **blades** attached to a **hub**; a **drivetrain**, usually consisting of a **gearbox** and a **generator**; a **tower** and foundation that support the structure; a **control system**; and supporting electrical equipment on the ground.

A wind farm is a group of turbines that generate electricity for one owner. The wind farm includes electricity collection grids of wiring and transformers and an overall wind farm control system that monitors the operations of all the turbines in the farm.

Capturing energy from the wind may appear simple, but in reality, wind turbines are among the most complex and largest moving mechanical structures. They operate in the largely hostile, relatively little understood, and highly unpredictable and turbulent part of the atmosphere near Earth's surface.

Aerodynamic forces on the blades create lift, causing the blades to rotate. These same forces that provide the energy source also flex the blades, bend the towers, and impose forces on the shaft and gearing of the drivetrain as the wind changes direction. The aerodynamic loads transferred from the wind to a wind turbine rotor must be transmitted through the rest of the structure to the foundation without causing undue loading and fatigue damage. (The damage caused when you keep bending a wire back and forth until it breaks.) At the same time these loads are being transferred, the maximum amount of kinetic energy must also be efficiently extracted from the in-flowing mass of air and converted to electricity by the generator.



This 34-meter (111-foot) blade designed for increased performance on Enron's 1.5-MW turbine will undergo fatigue testing at the National Wind Technology Center. It is the largest blade ever to be tested at the facility.

more energy from a given parcel of land. Manufacturers claim that decreased cost of energy from larger turbines may result from economies of scale in manufacturing. There may also be savings on balance-of-system costs and electrical station costs.

However, preliminary studies conducted in 2000 hinted that at least with current technology, bigger may not always be cheaper. In engineering, scaling up is usually not as straightforward as it might seem.

Cost-of-energy studies conducted by DOE's National Renewable Energy Laboratory (NREL), using newly developed scaling and cost models, show that as the size of turbines increases, the cost of energy decreases, to a point, and then begins to rise. Over time, the size of turbine associated with the lowest-cost option has increased as the costs of major components in large sizes have decreased. To lower the cost of energy further, WindPACT is trying to identify technological breakthroughs to improve performance for reduced costs. At the close of 2000, NREL sponsored a workshop in Golden, Colorado, to report on the technical findings and planned activities of WindPACT contractors.

BETTER BLADES

The wind turbine rotor, consisting of the blades and the hub (see page 5), drives the design of the rest of the wind turbine, because the airfoil and the mechanical properties of the blades determine what loads are transmitted to the other components in the turbine. New blade shapes designed by DOE's Wind

The WindPACT scaling studies have shown that commercial blades at the upper end of the current size range, 40 meters long (131 ft), are already pushing the limits of what can be economically achieved using conventional manufacturing methods and materials.

Program have increased wind turbine performance by as much as 30% over designs used just 10 years ago. Combined efforts of industry and federal laboratories have increased understanding of dynamic loads on structures, allowing more efficient designs and a decrease in component weight and cost.

In 2000, a WindPACT study conducted by Global Energy Concepts evaluated the structural properties for a wide range of aerodynamic designs and sizes of blades. This study quantified the limitations to the economical scaling of the current commercial approach to blade design and manufacture.

The scaling studies showed that commercial blades at the upper end of the current size range, 40 meters (m) long (about 131 ft), are already pushing the limits of what can be achieved using conventional manufacturing methods and materials. With existing technology, as the blades get longer, they get heavier faster than their ability to capture more energy. Energy capture increases by the square of the blade length. Weight, however, increases by the cube of blade length. Increased weight raises material and manufacturing costs in direct proportion. At the point where gravity forces acting on the blade become dominant, further escalation in blade weight will no longer be justified. New technologies are needed to defeat the weight and cost limits.

The scaling studies are directing the DOE Wind Program efforts to get beyond this cost barrier by developing new blade technologies. To make blades for larger machines without paying a cost premium for scaling up, designers must come up with fundamental changes in materials, manufacturing processes, and rotor designs. The program is funding work to explore new materials, such as carbon or glass-carbon hybrids, that could replace some of today's fiberglass, wood, and steel. Another path to improving blades is to develop and test new blade fabrication techniques. Work on manufacturing processes that improve fiber alignment and compaction and reduce voids in materials has been taking place at Sandia National Laboratories.

BETTER ROTORS

Other work begun in 2000 to develop new rotor designs could reduce the loads on blades and allow them to be lighter using conventional materials. The first step was to develop and assemble appropriate design models to evaluate the impacts of different rotor configurations on cost of electricity. Rotor configurations are being considered for each size turbine being explored under WindPACT —0.75 MW, 1.5 MW, 3 MW, and 5 MW. Then the researchers will make a dynamics model using the FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code developed under an NREL subcontract by Oregon State University to predict how the turbines will respond in each of about 30 different rotor configurations. Finally, the cost analysis will consider necessary capital cost, manufacturing cost, impact on operation and maintenance cost, and effect on performance of each rotor configuration.

Configuration options include the number of blades; the orientation upwind or downwind of the tower; the amount of movement or flexing allowed in the blades and the hub; and the way blades are used for speed and power control. Engineering calculations using these many configuration options will be completed in 2001. They will assess the impact on loads imposed, materials required, noise generated, ease of manufacture, and dynamic impacts on the rest of the machine. For example, using two blades rather than three changes the loads that are transferred to the rest of the machine. Whether the turbine faces upwind or downwind dictates important requirements for the rest of the turbine. Different methods of turning the blades or pitching to control rotor speed affect the loads that get transmitted to the turbine.

When the rotor design studies are complete, manufacturers and researchers will be able to determine the advantages of each rotor design, in light of the cost and performance variables considered. They will have new tools to estimate the impact on rotor designs and system dynamics of changes to rotor size and configuration. And the program will have identified rotor design issues that may be barriers to improving larger rotors. Future work could then tackle these barriers to scaling up wind turbines.

New rotor designs, when combined with improved materials and manufacturing techniques, could shift the lowest cost-of-energy point to larger sized rotors.

BETTER DRIVETRAINS

The drivetrain is another key component that offers great potential for innovation and must be considered when looking for cost savings. Today, most turbines use a gearbox to increase the shaft rotation speed (about 10 to 30 revolutions per minute [rpm]) as it comes from the turbine rotor in order to drive a standard generator at 1200 to 1800 rpm. As the capacity of these gearboxes increases toward 5 MW, the physical dimensions and weight of the gearbox increase dramatically. This increased weight adds to material costs and complicates the logistics of transport and installation.

To overcome this cost barrier to scaling up and to potentially reduce drivetrain costs in all machines, WindPACT contractors began looking at new drivetrain configurations for wind turbines. These innovative configurations could be from other technologies or ones that have never been tried. These concepts include the development of low-cost, low-speed drives that reduce the weight of equipment at the top of the tower. Such drives might also increase energy conversion efficiencies. Other avenues include advanced electronics that reduce losses during variable-speed operation.

In 2000, two contractors, Global Energy Concepts and Northern Power Systems, were working independently on preliminary design studies of seven drivetrain concepts. These studies consider the impacts of new approaches on driveshaft supports, gearboxes, gearing configurations, gear loading, gear fatigue, gearbox bearings, gearbox supports, generators, generator bearings, and generator supports.

The results of WindPACT design studies will be available to the entire industry. When results are published, the most promising design will be fabricated and tested. Additional benefits of these studies will be the expertise developed by the participating contractors and the tools developed for the analyses.

GETTING THE PARTS TOGETHER—LOGISTICS

In addition to scaling studies of wind turbine components in 2000, Global Energy Concepts looked at how costs might rise due to the logistics of transporting, assembling, and installing the pieces of larger machines. They began with a hypothetical wind farm site in South Dakota where 50 turbines would be installed. Five scenarios were considered, for a wind farm composed of turbines rated at 0.75 MW, 1.5 MW, 2.5 MW, 3.5 MW, and 5 MW.

For each of these turbine sizes, the researchers estimated, on the basis of scaling studies, the physical dimensions and weight of all the major components—blades, hub, drivetrain, drivetrain cover compartment, and tower. Component scaling was based on current wind turbine technologies. When they had specified the dimensions and weight of all the components, the researchers worked with experts in companies that have transported wind turbine components to installation sites in the United States.

Shipping costs are related to the type of transport that is required and available, such as rail, truck, or barge. For the hypothetical South Dakota wind farm (and much of the United States), only truck and rail are realistic options, and each has maximum weight and size limitations.

The study found that any load placed on a truck that increases the height of the load and truck combined to 4.9 m (16 ft) would likely encounter clearance problems with bridges or utility lines. Rectangular or circular loads have larger profiles, whereas triangular or vertical loads are easier to negotiate around low-hanging objects, such as streetlights, without the extra cost of temporarily removing the object. Removing obstacles to allow transport of large components can increase transportation costs dramatically. The study found that the height limit for tubular towers to be transported and erected by conventional equipment is 65 m (about 200 ft). A key problem is the diameter of the tower base: if it is too great (4.9 m above the road), it cannot be transported over the U.S. highway system. Another limitation is the size of crane required to lift the turbine to its place on top of the tower. Because of the angles and weights involved, massive cranes are required for turbines on towers taller than 65 m.

Using the cost analysis for assembling and moving the huge cranes required for each size turbine, researchers evaluated alternative methods used in other industries. Anticipating rising costs for installing taller towers and heavier machines, a study completed in 2000 looked at the feasibility of installing wind turbines without using cranes. They found that using one of several designs for climbing frames may be cheaper than using a crane, when turbine size reaches 2.5 MW. The results of this study will guide industry in reviewing alternatives to using costly cranes for large turbines. However, for larger wind farms, dedicated cranes still appear to be competitive.

These careful analyses of logistical issues are available to all wind turbine designers, who can proceed to design around the size-related cost increases for transportation, assembly, and installation of multi-megawatt wind turbines.

BALANCE-OF-STATION COSTS

In addition to the cost of the wind turbine components—blades, drivetrain, tower, etc.—associated costs of wind farm development are included in the cost-of-energy calculation. A WindPACT study completed in early 2001 looked at how the associated costs increased with the size of turbines used to develop a 50-MW wind farm. The researchers found that the largest of these balance-of-station costs is the foundation, pointing out an area for possible research to reduce costs for all machines.

The researchers also looked at the costs of service roads, maintenance buildings, and electrical systems. The overall conclusion was that balance-of-station costs for a 50-MW wind farm were not affected by the size of turbine—whether the farm consisted of ten 5-MW machines or more than 60 machines rated at 0.75 MW each.

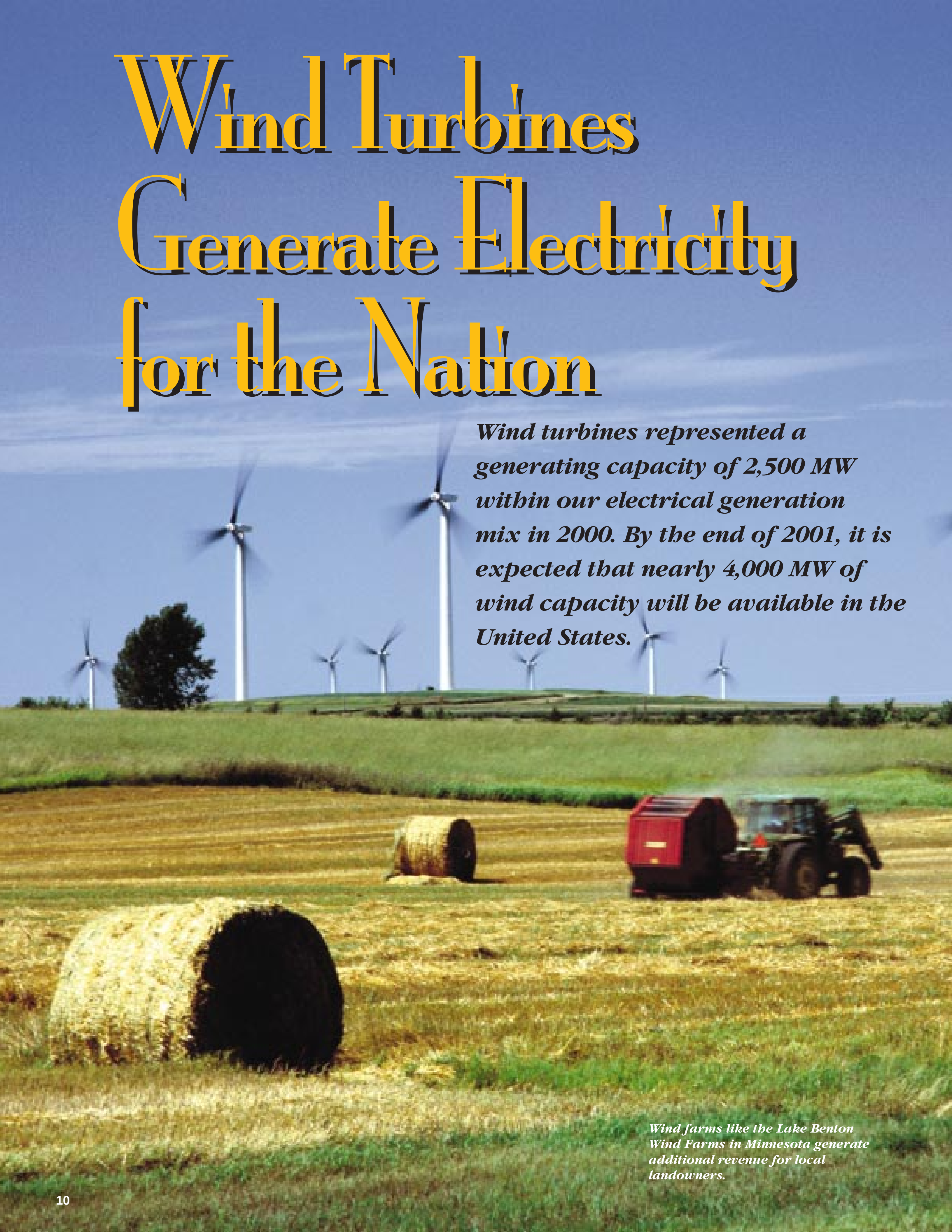
FINDING THE BEST SIZE TURBINE

The results of the scaling and design studies completed in 2000 are already available to U.S. industry. Placing the results of this research in the public domain should speed integration of the findings into the commercial designs of the future. In 2001, contracts to develop prototype components will be placed. By 2002, the test data from these prototypes will give industry a firm footing to proceed with developing turbines to produce electricity at \$0.03/ kWh at moderate wind speed sites. ◆

Researchers are looking for ways to control the costs of shipping, assembling, and installing the pieces of large turbines like Enron Wind Corporation's 1.5-MW turbine.

Wind Turbines Generate Electricity for the Nation

Wind turbines represented a generating capacity of 2,500 MW within our electrical generation mix in 2000. By the end of 2001, it is expected that nearly 4,000 MW of wind capacity will be available in the United States.



Wind farms like the Lake Benton Wind Farms in Minnesota generate additional revenue for local landowners.

WHILE RESEARCHERS IN LABORATORIES AND TEST SITES OF DOE'S WIND ENERGY Program and industrial partners develop the next generation of wind turbines, today's turbines are generating electricity and laying the foundation for wider use of this alternative energy option in the future. Today, manufacturers are offering warranties on performance, and the industrial infrastructure is maintaining availability of 98% to 99% for the latest hardware. Certification to international standards is opening world markets to U.S. wind energy products, and the market for wind energy is growing by 30% per year.

This market consists largely of customers who prefer to buy power from renewable sources of electricity generation and policy makers who encourage its introduction. The states of Alabama, Alaska, Arizona, Arkansas, California, Colorado, Florida, Hawaii, Idaho, Illinois, Indiana, Iowa, Kansas, Maryland, Massachusetts, Minnesota, Mississippi, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New York, North Carolina, North Dakota, Ohio, Oregon, Rhode Island, South Carolina, South Dakota, Tennessee, Texas, Vermont, Virginia, Washington, Wisconsin, and Wyoming have incentives that encourage development of renewable energy systems; many include wind generating stations. Financial incentives include exemptions from personal, corporate, sales, and property taxes; rebates, grants, and loans; and others.

Unlike most electricity generation technologies, wind energy developments are highly compatible with other land uses such as farming and ranching. Today's wind farms demonstrate that farmers can plow right up to service roads, cattle can graze around turbine pads, and landowners can realize additional revenues. In Iowa, for example, typical family farms have two to six turbines and receive up to 2% of the wind turbine's gross revenue from annual sales of power, or about $2,000 per turbine. At a time when farm economies are sorely strained, wind power is a welcome addition to bolster their power needs and their balance sheets.

In addition to lease payments, today's projects demonstrate other economic benefits for rural America. Local property taxes bring in about $1 million per year for each megawatt of installed capacity.

A Size for Each Application

Application: Homes, farms, water pumping, telecommunications sites, ice making

Rotor Size: 1–10 m (3–30 ft)

Output: 400 W–50 kW

Application: Village power hybrid systems, distributed power

Rotor Size: 10–50 m (30–164 ft)

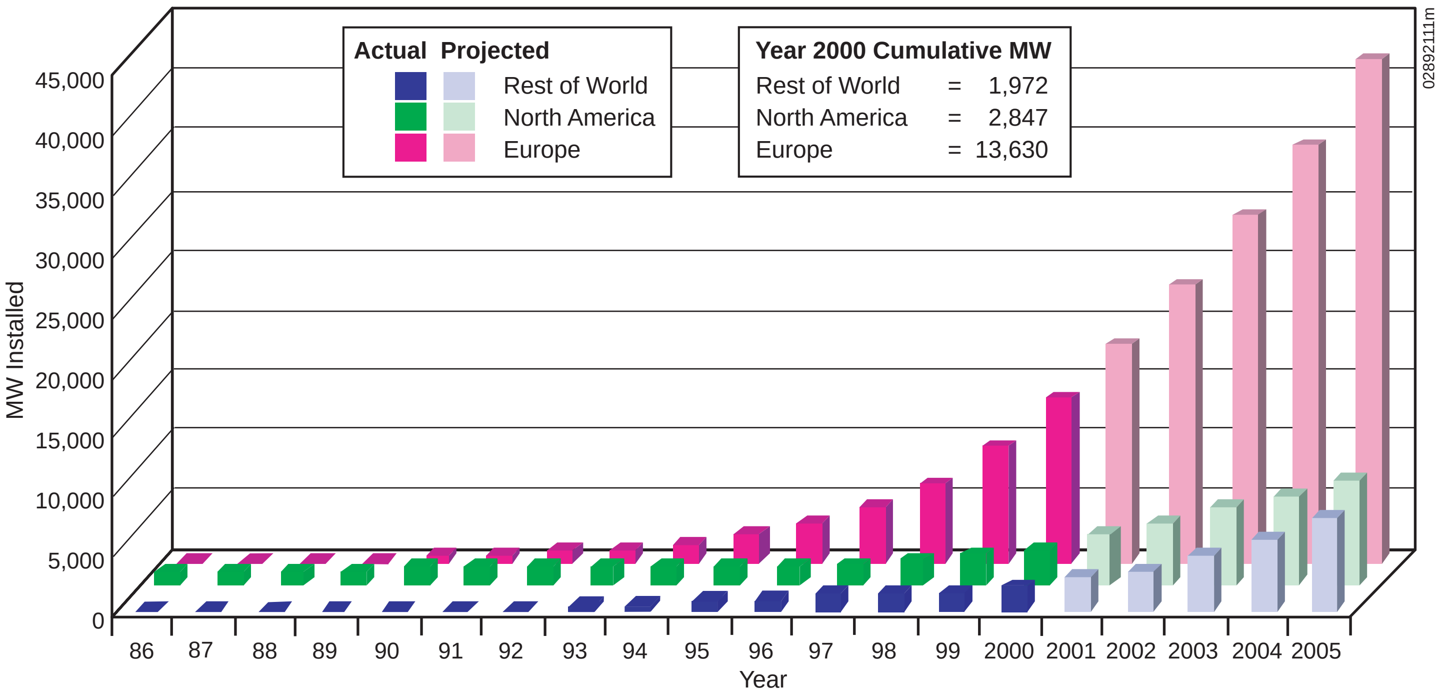
Output: 50–500 kW

Application: Central station wind farms, distributed power

Rotor Size: 50–120 m (164–394 ft)

Output: more than 500 kW

Growth of Wind Energy Capacity Worldwide



During construction, about two jobs per megawatt are added to the local economy, when local contractors install foundations, roads, towers, and electrical systems. After construction, as many as five permanent jobs are created for operating and maintaining each 50 to 100 MW of installed capacity. Growing demand for electricity in states such as California makes wind energy an attractive way to expand electrical supply. To quickly expand electrical generation capacity, wind plants can be installed and begin operating in less than a year.

The growing market for wind energy is an important part of the process to develop advanced technology that will eventually reduce the cost of energy from wind turbines. Data from large wind farm developments, for example, provide valuable operating experience to researchers seeking to improve system performance. Good performance records at these wind farms also lay the foundation for future projects. The DOE Wind Program works to expand the use of wind energy by providing current information on performance and by using data collected from operating turbines in ongoing research projects aimed at improving the technology. These data are used to assess impacts on utility systems and to understand issues associated with the integration of wind-generated electricity into the transmission and distribution system.

DOE's Wind Program works to expand the use of wind energy by providing current information on performance and by using data collected from operating turbines in ongoing research projects aimed at improving the technology.

TURBINE VERIFICATION PROJECT

Some utilities that own conventional electrical generating sources have installed wind-generating stations to expand their capacity. However, many utilities are concerned about increased reliance on wind energy because they have no experience with a power technology they cannot turn on and off at will. To help utilities in different geographic and climatic areas to gain experience with a wind project, DOE and the Electric Power Research Institute (EPRI) launched a project to validate wind turbine performance at utility installations. Reducing the cost to utilities with cost sharing and reducing the risk by providing technical assistance proved to be the right strategy.

Seven turbine verification projects have placed utility wind turbine projects in mountains, on plains, in deserts, on coasts, and in the tundra. Participating utilities share their experiences with other utilities at workshops and in technical reports. Reports published in 2000 presented the experiences of projects in Kotzebue, Alaska; Big Spring, Texas; Algona and Alta, Iowa; Springview, Nebraska; southern Vermont; and Glenmore, Wisconsin. The projects provide valuable information on the performance of new hardware developed under the DOE Wind Program.

Solving any technical problems with new hardware and problems related to geographic location paves the way for similar projects to be added in the years ahead. Several unanticipated technical issues related to the project locations were resolved through cooperation of the turbine supplier, the utility operator, and the DOE and EPRI engineers. For example, at the Central and South West Services wind farm in Texas, multiple lightning strikes in 1997 led to a cooperative effort to solve the problem. Working with DOE's National Wind Technology Center (NWTC), the National Lightning Safety Institute, Central and South West, and the manufacturer installed an improved lightning protection system in the communications cables and created better grounding around the turbines. Because of the turbine verification project reports on this activity, utilities throughout the Great Plains have reaped the benefits of Central and South West's experience with lightning hazards.

Opening potential markets in good locations with low-to-moderate wind speeds was the objective of the Wisconsin Low Wind Speed Turbine Project in Glenmore, Wisconsin. This joint undertaking of EPRI and four eastern Wisconsin utilities used turbines that had been modified for operation in low-to-moderate wind speed areas such as those of eastern Wisconsin. The turbines were also equipped with features for the cold weather of Wisconsin.

York Research Corporations working with Texas Utilities personnel in Big Spring, Texas, gain important insight into the operation and maintenance needs of a wind power plant through DOE's turbine verification project.

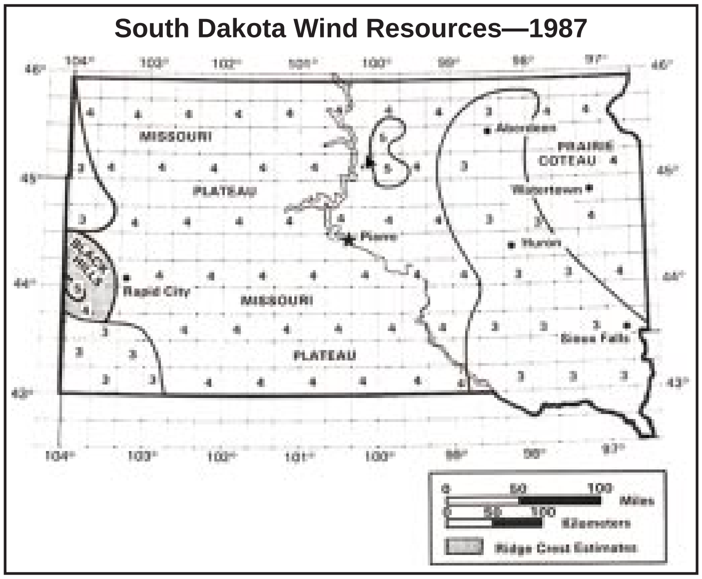
DOE's Wind Program will continue to support the collection and publication of data on these projects through 2001. Then the utilities will take over, as planned. Several of the utilities already have additional wind turbine projects under development.

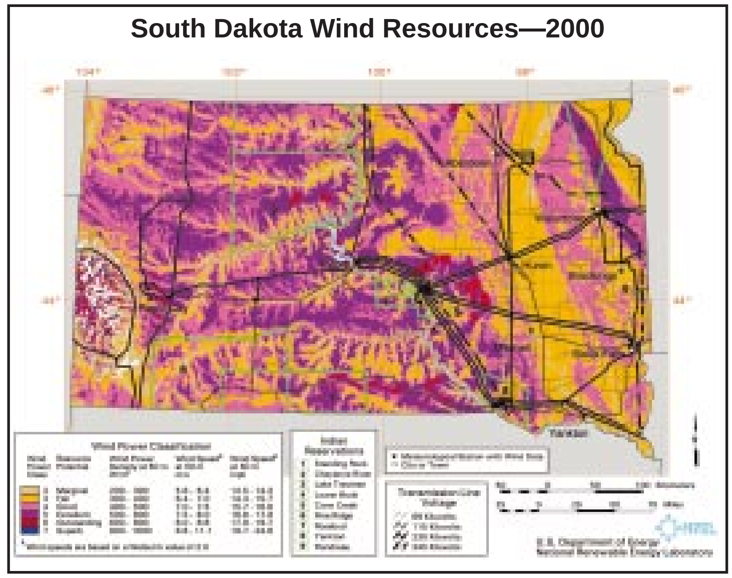
Building from the turbine verification project experience, a new project is planned to collect performance, operation, maintenance, and cost data for new technology. The new regional field verification project will verify the performance of advanced wind turbines across the nation in projects addressing new uses and new wind energy system owners. The projects will be targeted to regions without previous experience with wind energy and will involve state and local governments, turbine manufacturers, and users. A small amount of federal funding will reduce the total cost to participants of the project and support performance monitoring, verification, and information dissemination activities.

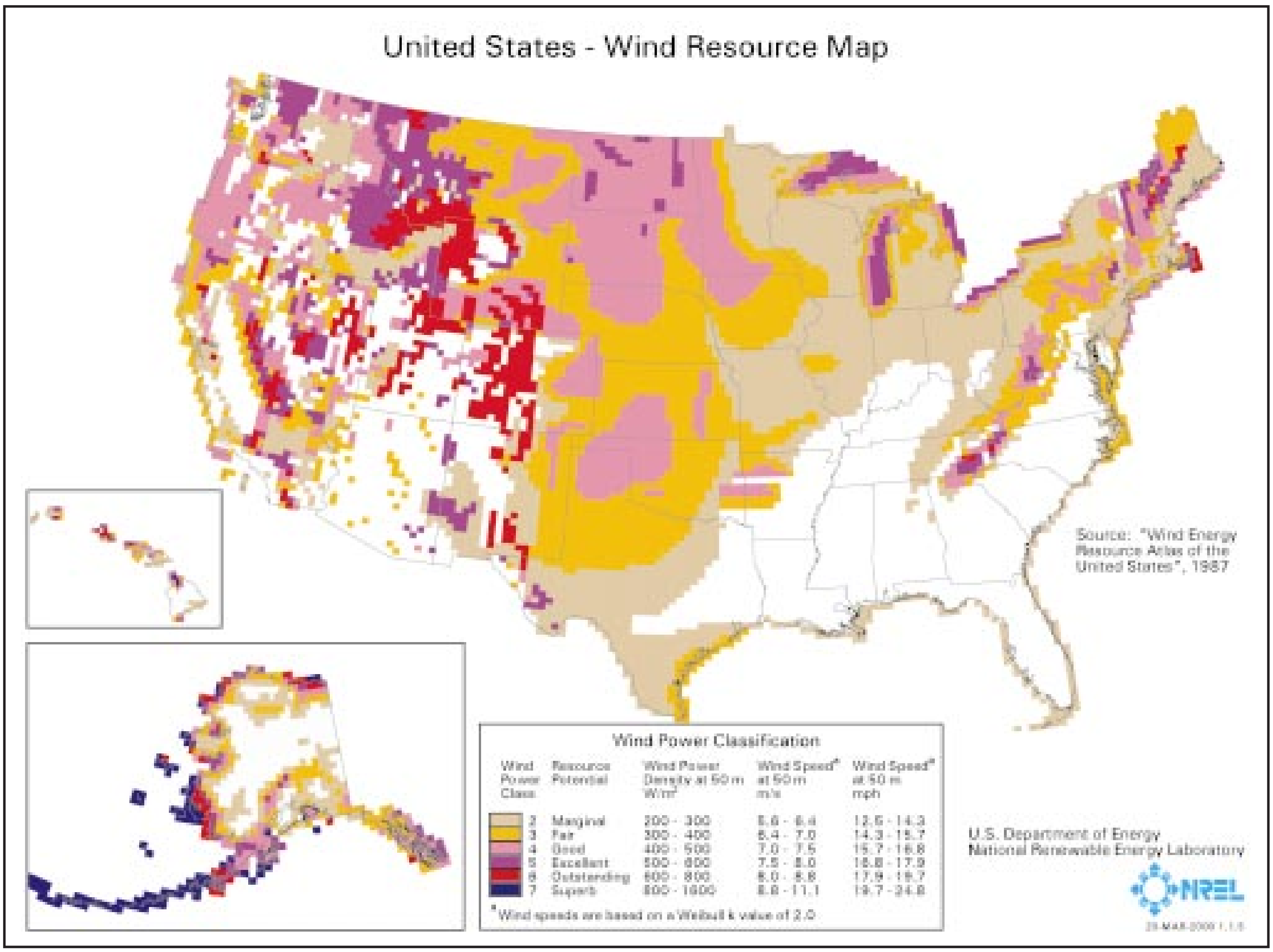
The regional field verification project will collect data on a broader range of applications than the original project. Some applications will use small wind turbines rated to generate up to 100 kW for homes, ranches, or remote places where electricity is needed. Some will use larger turbines connected to distribution lines. Still others will use large turbines in wind farm developments. In December, NREL issued a pre-solicitation notice for regional verification projects. The first projects will be selected in 2001.

ASSESSING THE WIND RESOURCE

All markets for wind turbines require an estimate of how much wind energy is available at potential development sites. Correct estimation of the energy available in the wind can make or break the economics of a wind farm development. To provide the best information possible, the DOE Wind Program has been assembling data sets and refining modeling techniques for three decades. In 1987, the program had enough information to publish the *Wind Energy Resource Atlas of the United States*. Since that time, researchers at NREL have continued to refine techniques to improve the information available to wind power developers at all levels, and over the past 5 years, have developed a computerized mapping system. In 2000, work continued on the system and two highly detailed resource maps of North and South Dakota were published to help guide state







Strong, frequent winds are ideal for generating electricity. The best resource areas are shown on maps incorporating wind speeds based on measurements taken throughout the year at monitoring stations and on estimations coming from the newest meteorological data and models. For a specific location, annual average wind speed and wind speed distribution are used to calculate the amount of energy in the wind blowing through a wind turbine's rotor per square meter of area. This is expressed as watts per square meter. From this calculation of the energy available in the wind, geographic areas as small as one square kilometer are assigned a wind power class from 1 to 7. State officials and developers use this information to find the best areas for wind development. Sites in wind power class 4 or higher are candidates for wind farm development. Class 2 sites or higher offer possibilities for adding small wind systems.

Partners Work in Today's Market

The DOE Wind Program works with industry, utilities, and groups such as the National Wind Coordinating Committee (NWCC), the Utility Wind Interest Group (UWIG), and the American Wind Energy Association (AWEA) to provide data, analyses, and support for wind energy initiatives. A long-term (5–10 years) strategic planning meeting with industry stakeholders was held in November 2000 in Washington D.C. to help industry in efforts to commercialize the technology.

The NWCC was formed in 1994 to help develop an environmentally, economically, and politically sustainable commercial market for wind power. The NWCC includes representatives from electric utilities and support organizations, state legislatures, utility commissions, consumer advocacy offices, wind equipment suppliers and developers, green power marketers, environmental organizations, and state and federal agencies. When it is time to take a stand on an issue, the NWCC strives to obtain a consensus from its members.

For example, in 2000 the NWCC formed a new subcommittee—the Credit Trading Working Group. Because cleaner air and reduced CO_2 emissions are not directly valued in the U.S. economy, wind energy and other cleaner, renewable energy resources do not realize their full value from energy markets. This "market imperfection" is perhaps one of the biggest challenges facing wind energy use in the United States, according to the NWCC. Their new subcommittee will educate NWCC members and others, including air-quality regulators, the wind industry, utilities, and the environmental community, about how trading of emissions credits may impact wind development in the United States. The NWCC aims to provide credible, balanced information on the emissions reduction benefits of wind energy and to support the rational implementation of air emissions trading requirements. For more information about the NWCC, visit their Web site at http://www.nationalwind.org/.

UWIG is a nonprofit corporation founded in 1989 to accelerate the use of wind power for utility applications. Membership, which has doubled in the past three years, is open to utilities and other entities that have an interest in wind generation. UWIG currently has 50 utility members in 17 states, as well as academic, government, and corporate members. UWIG experts in utility analysis participate in NWCC committees and contribute to standards development through the Institute of Electrical and Electronics Engineers to resolve issues of wind energy development and utility interactions. UWIG also works with DOE on activities that provide technical support to assist utilities with integrating wind energy into their generation mix.

For example, in 2000 UWIG helped administer NREL's Utility Wind Resource Assessment Program (U*WRAP). By supporting utilities conducting wind resource assessments, U*WRAP is increasing the quality and quantity of wind data available to utilities. Better wind data helps them evaluate the contribution wind energy could make to their generation mix. In another activity, UWIG and the DOE Wind Energy Program sponsored a technical workshop "Wind Energy for the Electric Power Mainstream" at the National Energy Technology Laboratory in Morgantown, West Virginia. For more information about UWIG, visit their Web site at http://www.uwig.org/.

AWEA is a national trade association that represents wind power plant developers, wind turbine manufacturers, utilities, consultants, insurers, financiers, researchers, and others involved in the wind industry. In addition, AWEA represents hundreds of wind energy advocates from around the nation. AWEA estimates that during the year 2000, new wind energy generating installations increased by 3400 to 3500 MW worldwide, representing annual sales of close to $4 billion and boosting total capacity to about 17,000 MW. To promote this market, AWEA held its annual technical and market development conference, WINDPOWER 2000, in Palm Springs, California. This conference is attended by all parties involved in the use of wind energy. For more information about AWEA, visit its Web site at http://www.awea.org/.

and local policy decisions about implementing wind energy systems.

The new maps have a resolution of 1 square kilometer in contrast to the old maps that have a resolution of 25 square kilometers. More data sets are available for analysts to apply, and the new system treats terrain in consistent patterns, which reduces labor required while increasing accuracy. Because of this, the new maps show more variablility in wind resource than the old maps to help developers better identify promising areas for wind energy development. Perhaps most important, the maps use Geographic Information System (GIS) software. Using GIS, researchers can add overlays of significant features, such as power lines, park boundaries, and roads to the wind resource maps.

Because wind resource assessment technologies have improved greatly in recent years, researchers began planning an updated version of the U.S. wind atlas in 2000. This project, to be supervised by NREL, will take advantage of the new mapping system and produce more maps with a resolution down to 1 kilometer. It will also incorporate new meteorological, geographical, and terrain data. The program's advanced mapping of the wind resource is another important element necessary for expanding wind-generating capacity in the United States.

Even in regions with good-to-excellent wind resource for utility-scale applications, it is important to know the level of wind generation available at a given time. Wind power plants generate varying amounts of electricity depending on wind speed

Turbine Certification

In the rapidly developing market for wind turbines, turbine buyers at home and abroad like the assurance of turbines with certification. Local building authorities, project financiers, and insurance companies are asking for certification to reduce their risk before projects move forward. To compete overseas, U.S. manufacturers must have their products certified to standards adopted by other nations.

In certification, an independent party gives written assurance that a product, process, or service conforms to specified requirements. In the case of wind turbines, the third-party certification body assures that turbines perform according to standards developed by international bodies such as the International Electrotechnical Commission (IEC). The third party must be accredited by a recognized authority as impartial and capable of the technical accuracy that is required for the standard.

Testing and design reviews can be performed only by organizations with in-depth knowledge of wind turbine technology. At present, DOE's National Wind Technology Center is the only accredited testing laboratory in the United States that can provide testing and analysis for the certification of wind turbines for international and domestic markets. The NWTC is accredited by the American Association of Laboratory Accreditation for conducting wind turbine power performance, structure, and noise certification testing.

The certification test results from the NWTC are used by the U.S. certification agent, Underwriters Laboratories (UL), as the basis for certifying the designs of U.S. industries' machines. Founded in 1894, Underwriters Laboratories is the nation's undisputed leader in product safety and certification. This independent, non-profit organization applies more than 14 billion of the familiar UL marks to products worldwide each year. More than 17,000 product types produced by more than 40,000 manufacturers are evaluated by UL. Integral to UL's certification of wind turbines are the design evaluations and wind turbine tests conducted at the NWTC.

In 2000, the NWTC performed certification tests for turbines of widely varying power output. Engineers tested the Southwest Windpower 0.4-kW turbine for safety and function, duration, and power performance. Tests were completed for Enron Wind's 750-kW turbine, verifying power performance, power quality, noise, dynamic characterization, blade durability, and drivetrain characteristics. The Enron 750i commercial turbine is also undergoing field tests to provide data for certification and design evaluation. Enron is seeking UL certification of power performance, power quality, and structural loads with the help of tests performed by NWTC engineers. Enron plans to begin the certification process for its 1.5-MW turbine in 2001. The Atlantic Orient 50-kW and Northern Power 100-kW turbines coming out of the Wind Program's turbine development programs have also been undergoing tests that will lead to certification by UL.

International certification relies on standards that are continually updated and expanded. This standards development process is conducted by international committees of experts, the foremost being the IEC, to develop appropriate international standards and testing procedures. Researchers in DOE's Wind Program work closely with the International Electrotechnical Commission (IEC) to assure reciprocity and acceptance of U.S.-developed analytic tools used in the process of designing turbines. In addition to an active role in standards development, DOE's Wind Program is developing the capability to conduct all the required certification tests in accordance with IEC standards.

Certification is the last step in the process of developing a new turbine design. As new designs are developed, the DOE turbine research project requirements match the IEC certification requirements. Companies participating in these cost-shared development contracts can expect to finish the project with all the documentation and reviews needed to satisfy the IEC.

Companies meet with NREL and the certification body early in the project to lay the foundation for certification. All important design steps are documented and reviewed by NREL engineers. If deficiencies exist that may hinder certification, the design phase continues with new engineering calculations, tests, or possibly redesign of major components. By the end of the turbine design projects, the new turbines will meet the DOE cost and performance goals as well as all certification requirements to successfully compete in the United States and abroad.

and direction. Accurate wind forecasts can help integrate wind energy into a utility's energy mix in two important ways: first, by allowing utilities to schedule complex power generation mixes to meet consumer electricity needs, and second, by allowing electricity sellers to commit a certain amount of power at specific times and receive a fair price for their product.

Results from certification tests like this static lay test being conducted on a blade at the NWTC are used by Underwriters Laboratories as the basis for certifying the designs of U.S. industries' machines.

To help provide U.S. developers with tools for forecasting the quantity of wind-generated electricity that can be produced in a particular time period, the Wind Program supports development of wind forecasting systems. In 2000, researchers at NREL hosted an experts' meeting sponsored by the International Energy Agency to review the worldwide experience in wind forecasting. The meeting may result in international cooperation to improve modeling techniques that would enhance ongoing efforts at NREL. In addition, researchers at the NWTC are working with EPRI and consultants to plan a Texas/California wind forecasting project to develop forecasting tools. The Wind Program is also working with the National Oceanic and Atmospheric Administration's Forecast Systems Laboratory to build on work completed in 2000 to improve measures of forecast accuracy and to try to assemble forecasts and probabilistic wind forecasting tools.

Another area of research is prompted by the increasing size of wind turbines and the accompanying heights of their rotors above the ground. It has long been known that in some areas, such as the western Great Plains, a low-level jet stream forms in the nighttime boundary layer. This jet stream, while providing good winds, can also produce intense wind shears and "organized" turbulence that can adversely affect wind turbine operations. When wind turbine hubs were only 50 m high, the jet stream was not as much of an issue. But now, multi-megawatt turbine hubs reach as high as 65 or 80 m and future machines may reach up to 120 or even 150 m (500 ft). There is already some evidence that conditions related to the nighttime low-level jet may be causing some turbines to shut down because of fault conditions in the early evening hours and then remain off for the balance of the night, resulting in lost energy production. In order to provide wind turbine designers and operators with much needed data on this phenomenon, researchers in the Wind Program are planning a detailed experiment to study the low-level jet and its impacts on large wind turbines. The study will be conducted where the jet stream is most likely to occur—southern Kansas and northern Oklahoma, where they plan to erect a highly instrumented, 200-m tower to begin accumulating data in 2002. ◆

Increasing Wind Energy Use

Putting together wind energy projects demands a complex sequence of events and the cooperation of many interests, including regulatory bodies. In addition to its research and development activities, DOE's Wind Energy Program provides technical support with the aim of increasing the use of wind energy nationwide. This past year, DOE assembled a team of experts who worked with the DOE Regional Offices to sponsor conferences, develop training workshops, and target technical assistance for projects across the country.

Native American Anemometer Loan Project

There are more than 700 Native American and Native Alaskan villages and corporations located on 96 million acres in the United States. Many of these tribes and villages have excellent wind resources that could be developed to meet their electricity needs or to sell to other communities. However, several key issues must be addressed, including the lack of wind resource data for most tribal lands. To remedy this problem, NREL and the Western Area Power Administration provide anemometers and installation equipment for American Indian tribes to borrow to measure the wind resource on tribal lands. Reducing the cost of quantifying the wind resource on tribal lands should lead to pinpointing the best wind resource areas for development.

Technical Assistance

One of the objectives of the Wind Energy Program is to provide technical assistance to policymakers when it can make the most difference. For example, when the Colorado Department of Public Health and Environment, Air Pollution Division, found that a large company in Colorado was violating air pollution prevention regulations, a noncompliance penalty and civil penalties were assessed. To offset these penalties, experts from NREL demonstrated that purchasing wind-generated electricity would qualify as a U.S. Environmental Protection Agency supplemental environmental project. As a result, the company is purchasing electricity generated by wind turbines from the local utility. Over the next five years this arrangement will avoid the burning of 1,820 tons of coal.

Federal Facilities Market

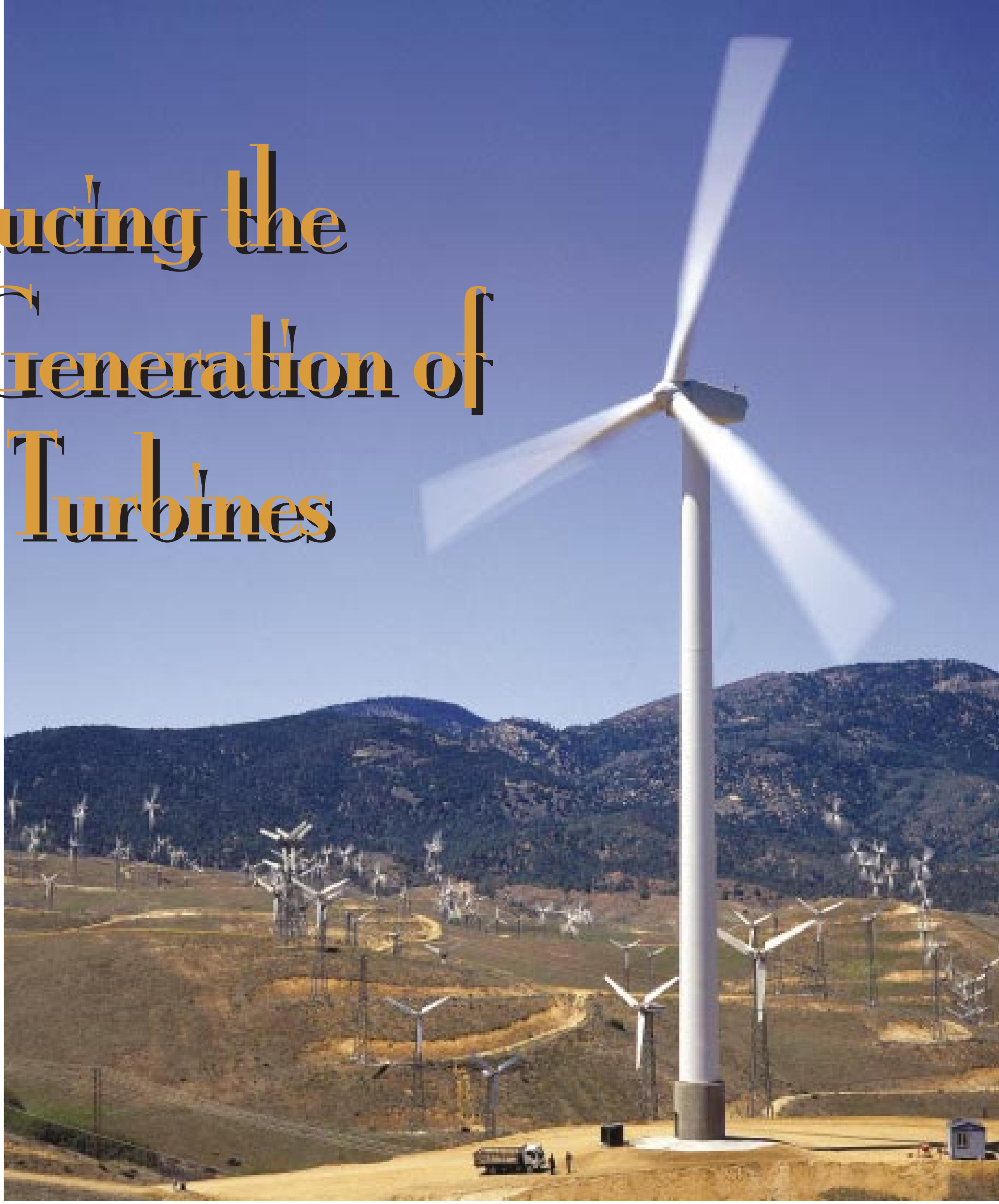
By coordinating representatives of 30 federal facilities in the Denver area, wind energy experts from NREL, working with DOE's Federal Energy Management Program, Golden Field Office, and the Denver Regional Office were able to get commitments to buy a total of 10 MW of wind-generated electricity. The agencies will buy their electricity from the Xcel Energy's Wind Source program in Colorado. DOE offices will help the agencies improve the energy efficiency of their facilities. The resulting cost savings will be used to pay for the small additional cost of wind power. Using this clean electricity will have the same effect as erasing 54 million miles each year in automobile travel.

Workshops and Information

Technical information and organizational contacts are key features of the Wind Powering America Web site that has been available since June 1999 (www.eren.doe.gov/windpoweringamerica). Workshops such as the one held in Lawrence, Kansas, in July 2000, were also important forums for wind energy information dissemination. By the close of 2000, similar workshops had been conducted in North Dakota, Montana, Alaska, Puerto Rico, Wisconsin, South Dakota, and Pennsylvania.

The Wind Energy Program's team of experts works with the DOE Regional Offices to get the message of economic opportunity through wind resource development to American farmers, Native Americans, and other rural landowners.

Introducing the Next Generation of Wind Turbines



Enron's new variable-speed, 1.5-MW turbine incorporates innovative electronics and aerodynamics.

Prototypes are proving that the next generation of wind turbines will soon be delivering electricity for lower cost.

WHETHER A SINGLE SMALL TURBINE GENERATES ELECTRICITY FOR A communications relay station in Alaska, a group of turbines supplies power to a utility distribution line, or a wind farm stretching across hundreds of acres feeds electricity into a high-voltage transmission line, the next generation of wind turbines will provide affordable, clean power in the years ahead. To create the wind turbines now being tested, designers have mixed and matched innovative components with proven technology. Researchers expect the resulting machines to be the least expensive and most efficient generators for a wide variety of jobs. To bridge the gap between current technology and the next generation of both large and small turbines, DOE and industry are building and testing prototypes that will eventually reach the growing market for alternative generation sources.

LARGE WIND TURBINES

To speed development of turbines that can compete in the electricity generation marketplace without subsidies, the DOE Wind Program began cost-shared partnerships with U.S. companies in 1997. The Wind Turbine Company (WTC), Belleview, Washington, and Enron Wind Corporation (formerly Zond), Tehachapi, California, designed, built, and tested a new generation of advanced utility-scale wind turbines. In 2000, both companies installed proof-of-concept turbines as

Field tests on the Wind Turbine Company's proof-of-concept, 250-kW turbine conducted at the NWTC showed that the new design significantly reduced the loads on the turbine's components.

The bane of wind turbine designers has been dealing with parasitic loads (drag) in the wind.... Our design deflects or mitigates parasitic loads by allowing the blades and the tower to bend.

— Ken Deering, VP Engineering, The Wind Turbine Company

part of the DOE/industry cost-shared turbine development. After tests on these first turbines, the companies will refine their designs and build prototype machines for continued testing. Finally, the prototypes will evolve into production models of commercial advanced wind turbines.

WTC designed an innovative machine with a downwind rotor and individually hinged blades. This design, along with a "soft" tower, is a new way to reduce loads on the other components of the wind turbine. Some of the loads are dissipated when the hinged blades flex and the tower bends slightly. This effectively reduces loads transferred to other components of the wind turbine, which can then be both lighter and less expensive.

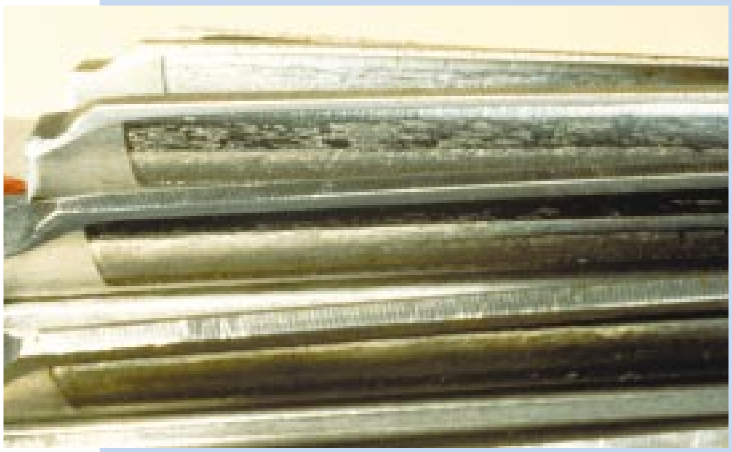
WTC installed a 250-kW proof-of-concept version of a 750-kW turbine at the National Wind Technology Center (NWTC) in April 2000. Field tests on the heavily instrumented turbine show that loads encountered by the turbine with the hinged blades were, indeed, lower. In fact, they were even less than those predicted by computer simulations. Following these successful tests, NREL and the California Energy Commission agreed to support development of a second, larger turbine that will become the prototype for commercial production. For this 750-kW machine, a longer rotor blade will be developed. That development effort will continue through 2001.

Another turbine resulting from the next generation turbine development effort is an Enron variable-speed, 1.5-MW turbine. Unlike constant-speed turbines, in which the rotor speed cannot vary, variable-speed turbines can respond to changes in the wind and thus capture more of the energy in the wind to generate electricity. Constant-speed rotors must be designed to resist high loads from wind gusts. Enron's variable-speed PowerMax^{TM} system absorbs the loads from gusts and converts them to electric power. Rotor speed is controlled by adjusting blade pitch. Generator torque is controlled through the frequency converter. This combined control strategy allows higher rotor speeds in strong,

Testing Highlights

The specialized testing services at the NWTC support turbine development partnerships by providing empirical data to compare with the predictions of design models.

Several tests helped refine gearbox design in 2000. One of the tests looked at ways to arrest micropitting of gear teeth in wind turbine gearboxes. Micropitting is caused by high-contact pressure at microscopic points along the gear teeth. Once the surface cracks begin, flaking of the surface layer can spread, eventually causing serious operational problems. Researchers began with a design known to be prone to micropitting and changed test conditions such as lubricants to see if they could arrest the process. In the field, it would take a long time to measure any results from changes in lubricants. The dynamometer test stand allows them to run a test turbine at full power, constant speed, and constant temperature to see how changes affect micropitting. Preliminary results show that micropitting can be drastically reduced. The information can be used to extend the life of wind turbine gearboxes.



Tests conducted at the NWTC look at ways to arrest micropitting (flaking of surface layers shown on a typical helical gear above) on wind turbine gears that can lead to serious operational problems.

Another test provided an empirical check on predictions of design models for the contact pattern where two sets of gears mesh. The contact pattern changes as the gearbox reaches rated load. To test contact at rated load, the gear surfaces were painted and the gearbox on the dynamometer test stand was driven to rated load. After the test, the surfaces were examined for uneven wear on the paint. This testing led to a correction of 0.003 cm in the surface of the gear teeth.

In 2000, wind turbine components such as blade roots and hubs were also tested in the NWTC's structural test laboratory. Accelerated tests of a new manufacturing technique called pultrusion were conducted on the blades slated for use on the 50-kW turbine under development. Repeated fatigue loading of the blade until it cracked helped blade designers evaluate their design assumptions and manufacturing techniques. The blade was much stronger than necessary for the anticipated loads on the turbine. Static-strength tests also revealed that the maximum strength loading the blades could withstand far exceeded what the turbine would ever experience. The material and manufacturing technique show great promise for wind turbine applications. These results indicate that the blade costs could be reduced while maintaining an ample margin of safety.

In related work, engineers at the NWTC built a special environmental chamber to test the performance of the studs embedded in blades of the North Wind 100 cold weather turbine. The studs connect the blades to the hub, and their performance is crucial to turbine durability. The strength of the studs in cold weather could not be found in standard engineering tables because there were no data for the performance of materials at very cold temperatures. To get the data designers needed, NWTC engineers designed an environmental chamber that fits around the existing blade test stand. Tests to failure under varying conditions down to -60 degrees F showed that the stud connection was actually stronger under cold conditions than at room temperature and met all design strength requirements for the 100-kW turbine. The environmental chamber could also be used to test material performance under hot and humid conditions.

Engineers at the NWTC built a special environmental chamber to test the performance of the studs embedded in blades of the North Wind 100 cold weather turbine. The chamber will test components at temperatures as low as -60 degrees F and can also be used to test material performance under hot and humid conditions.

The next generation turbine project has been instrumental in furthering the development of wind technologies that lower the cost of producing clean, renewable electricity.

— Craig Christensen, VP Engineering, Enron Wind Corporation

gusty winds, thereby reducing torque loads in the drivetrain.

This larger and more advanced version of the successful Z-750 series incorporates both innovative electronics and aerodynamics. It is expected to cost less to build, install, and operate than conventional turbines. Enron installed a proof-of-concept version of this 1.5-MW turbine at their wind farm in Tehachapi, California, where engineers from the NWTC tested the power performance, power quality, and acoustic noise. The tests show that it generates high-quality power that is fully compliant with the Institute of Electrical and Electronics Engineers IEEE-519 standard for power quality. In addition, acoustic noise tests proved the machine to be one of the quietest turbines of its size.

Enron's 1.5-MW turbine will be the first machine of this size to be produced commercially in the United States. By the close of 2001, Enron expects to have 350 of these machines installed around the country.

Rigorous field tests show that both the WTC and Enron proof-of-concept turbines generate the expected amount of power while keeping the stresses on the turbine low. These innovations should help reduce the cost of energy by increasing turbine output and reducing manufacturing costs.

SMALL WIND TURBINES

In the United States, 24% of the population lives in rural areas, and a growing number of people live in remote areas not served by electric power lines. Around the world, an estimated two billion people do not yet have access to electricity. In many of

Innovative Subsystems

This Northern Power Systems North Wind 100 turbine recently installed at the NWTC south of Boulder, Colorado, will be tested by a certification team for power performance, power quality, and noise. The team will also conduct safety and functions tests.

A series of partnerships with industry completed in 1999 under innovative subsystems contracts have resulted in viable U.S. products able to deliver wind-generated electricity at a competitive price.

One contract with Second Wind, Inc., produced a computerized control system called SCADA (Supervisory Control and Data Acquisition) that is being sold to wind farm operators around the world. This system can monitor current wind conditions and the power output of each individual turbine. It allows operators to see the entire power plant at one time by displaying a map of the turbines. Second Wind's SCADA systems now monitor turbines in Utility Wind Turbine Verification projects in Kotzebue, Alaska; Algona, Iowa; Springview, Nebraska; Big Spring, Texas; and Glenmore, Wisconsin.

Another success story of the innovative subsystems project is the direct-drive generator developed by Northern Power Systems that is being incorporated into the North Wind 100 cold weather turbine. Generators that work at the same low rotational speeds as wind turbine rotors hold promise for better performance at lower cost because the gearbox can be eliminated. Besides the component cost savings, having no gearbox is a plus in extremely cold weather such as in Alaska, where the mercury can plunge to -80 degrees F. At these cold temperatures, lubricants in the gearbox can solidify and prevent the turbine from operating.

these locations, the value of electricity is extremely high, and most ways to generate it are costly and bring pollution as well as rising fuel costs. Beginning to supply this potentially huge market, several U.S. companies now manufacture small wind systems with output up to 100 kW. Such turbines can operate in remote locations with low-to-moderate wind speeds.

The small machines available today are designed for high reliability and unattended operation. Because of these requirements, manufacturers on their own have been hard pressed to experiment with the significant new technologies that have become available over the past 15 years. In 1996, DOE responded to requests from the industry to support improvements in small-machine technology such as improved airfoil designs, neodymium-iron-boron magnets for smaller generators, and new, lighter materials.

The DOE project for small turbines follows a slightly different strategy from that of projects for large turbines. This altered strategy is necessary because the aerodynamic and structural design codes used to design large turbines need to be modified based on wind tunnel tests to predict loads on small turbines. Careful design reviews, pre-prototype and then prototype construction, and testing are more effective for small machines than the extensive modeling exercises performed before large machine proof-of-concept turbines and prototypes are built. In addition, because the scale of components is so much smaller than for large machines, several pre-prototype and testing phases can be performed on a small turbine design for moderate amounts of money.

The small wind turbine project promotes an engineering process rather than specific products. Researchers at the NWTC and Sandia work to reduce the cost of energy from machines with peak power ratings of 0.4–100 kW. Specific machine cost goals depend on the type of turbine, the nature of the operating environment, and the demands of the application. In 2000, companies were developing smaller turbines for both grid-connected and off-grid power generation.

One objective of the small wind turbine project is to develop a low-cost, high-performance wind turbine for charging batteries for homes, farms, or businesses not connected to the utility power grid. To meet this objective, Southwest Windpower, Flagstaff, Arizona, is reviewing the design of an early prototype 6-kW turbine. (The design was acquired from World Power Technologies, Inc.) Southwest Windpower will install a pre-prototype in Flagstaff, Arizona, in 2002.

Bergey Windpower is testing a larger turbine that incorporates features of their successful small turbine. Here, the Bergey XL.50 turbine's alternator is being tested on a dynamometer at their Norman, Oklahoma, facility for power production and rotor speed.

To develop a 10-kW machine for charging batteries, WindLite Company, located in Norwich, Vermont, is reviewing designs that will incorporate a permanent magnet generator and fiberglass blades. Testing on turbine components (blades, alternator, etc.) will begin in 2001.

Another project is developing a highly reliable 50-kW wind turbine to charge batteries for power systems far from an electric grid. To meet this project objective, Bergey Windpower has been designing a larger turbine that incorporates features of their very successful small turbine design. In 2000, the company installed a 50-kW pre-prototype turbine at its factory in Norman, Oklahoma. Company President Mike Bergey says, "This is the first wind turbine of its size to incorporate the passive controls and simplicity of design that have given our smaller wind turbines their high reliability." The turbine is undergoing tests for power production, rotor speed, noise production, wind tracking, and the ability to turn itself off in high winds. Technicians from NREL have tested the blades at the NWTC and found that they exceeded minimum requirements by about 75%. Tests on the first prototype will begin at the NWTC in 2001.

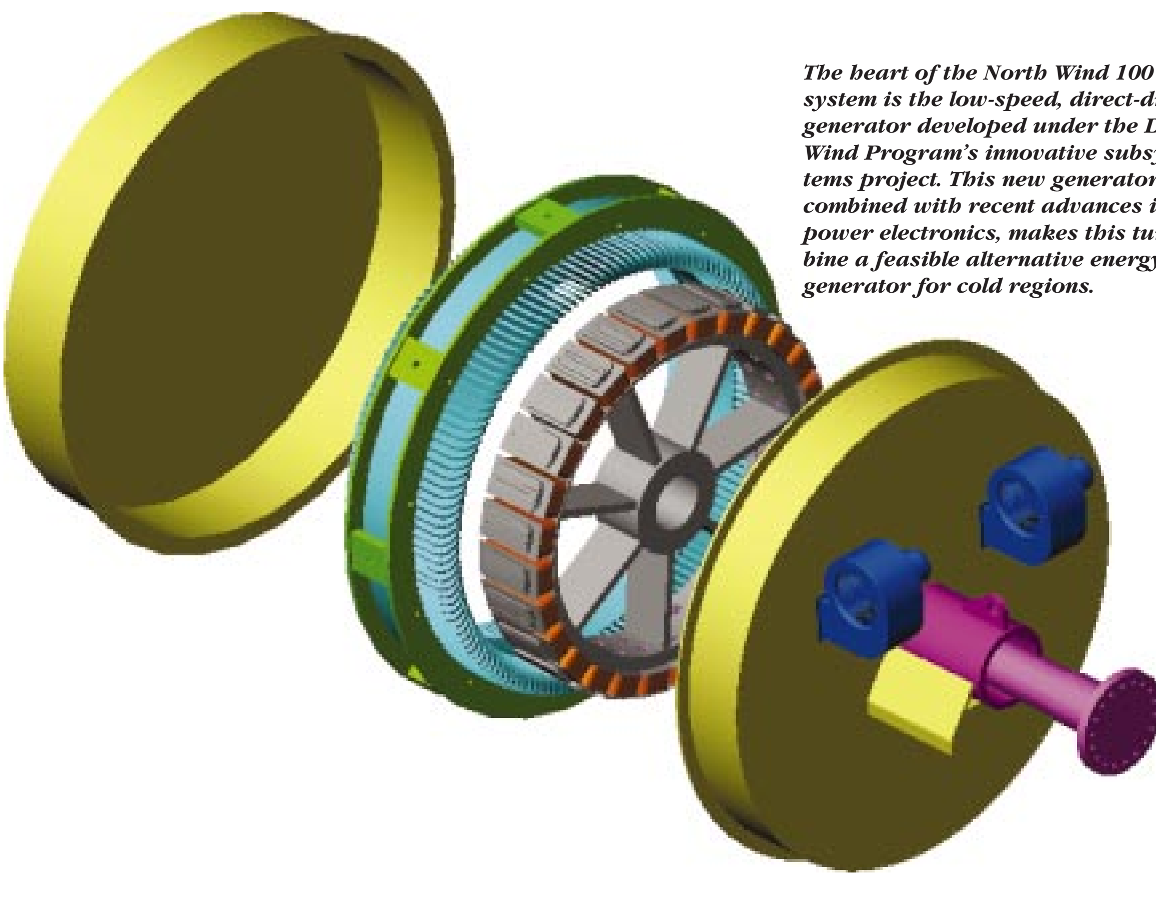
Another key project objective is to develop a cost-effective, 50-kW turbine for community power systems in combination with diesel generators. Atlantic Orient Corporation (AOC) has also been working under this contract to reduce the cost and

Engineers conducted tests on the Atlantic Orient Corporation's 50-kW turbine at the NWTC to prepare the machine for certification.

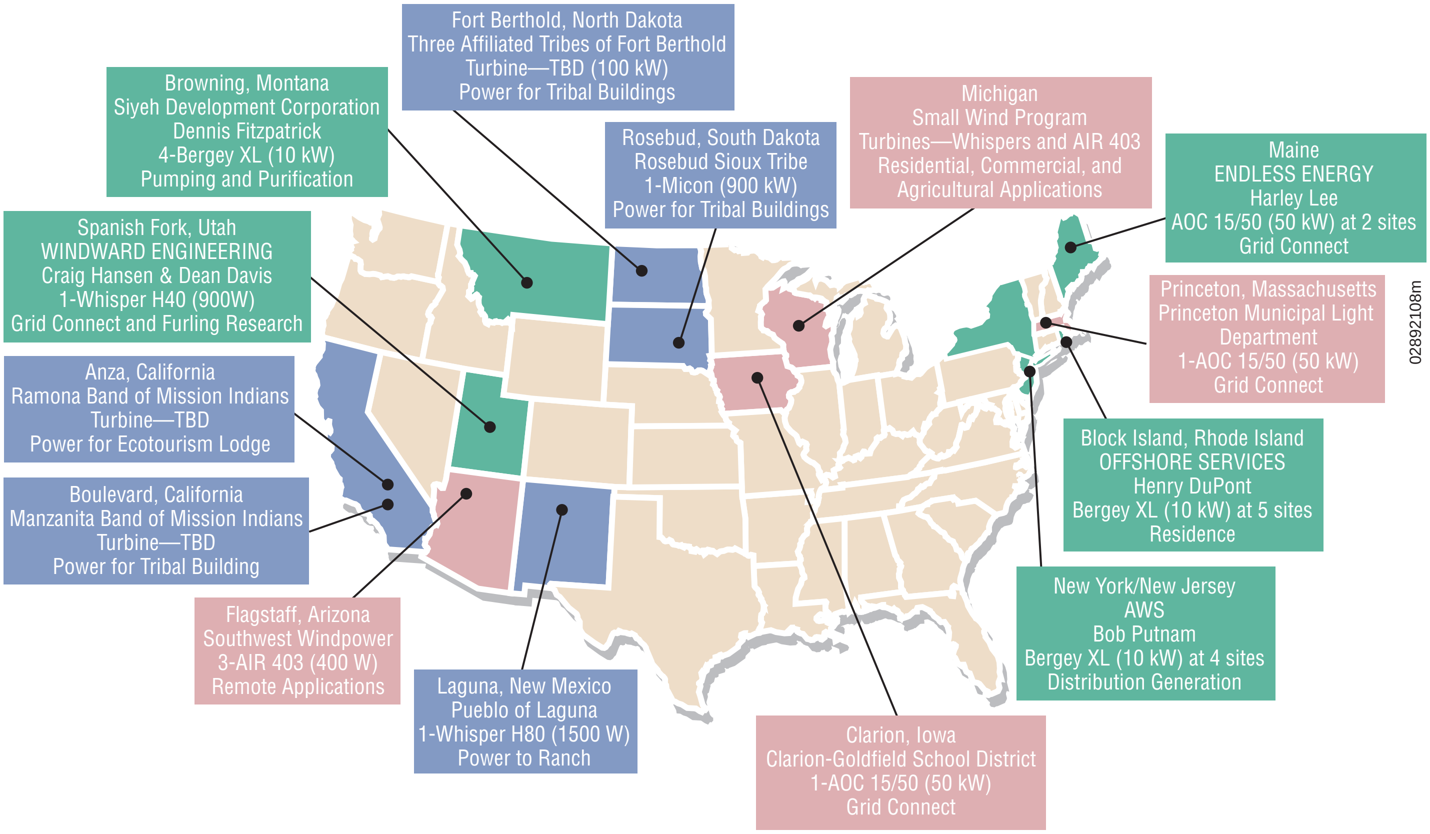
increase the reliability of its AOC 15/50 wind turbine. Versions of this 50-kW turbine modified for cold weather conditions have been operating at a turbine verification project site in Kotzebue, Alaska, since 1997. Several key tests were completed in 2000 to complete design certification and prepare the machine for certification. NWTC engineers conducted tests on the prototype turbine installed at the NWTC.

In frigid regions, remote villages or research stations often rely on diesel generators for electricity. Diesel fuel is very expensive in remote areas and generators can pollute the air, land, and water of these fragile environments. To provide a durable alternative to diesel generators, the Northern Power Systems' North Wind 100/20 was commissioned by the National Science Foundation, the National Aeronautics and Space Administration (NASA), and DOE. The special features of this turbine include a direct-drive design that requires no gearbox or lubricating oil, tilt-up assembly that does not require a crane, and enclosed areas for climbing the tower and maintaining the turbine. This turbine, designed for unattended operation, can generate enough electricity for up to 50 average homes.

Northern Power Systems, Waitsfield, Vermont, received an R&D 100 Award in 2000 for this innovative use of the advanced direct-drive generator and



The heart of the North Wind 100 system is the low-speed, direct-drive generator developed under the DOE Wind Program's innovative subsystems project. This new generator combined with recent advances in power electronics, makes this turbine a feasible alternative energy generator for cold regions.

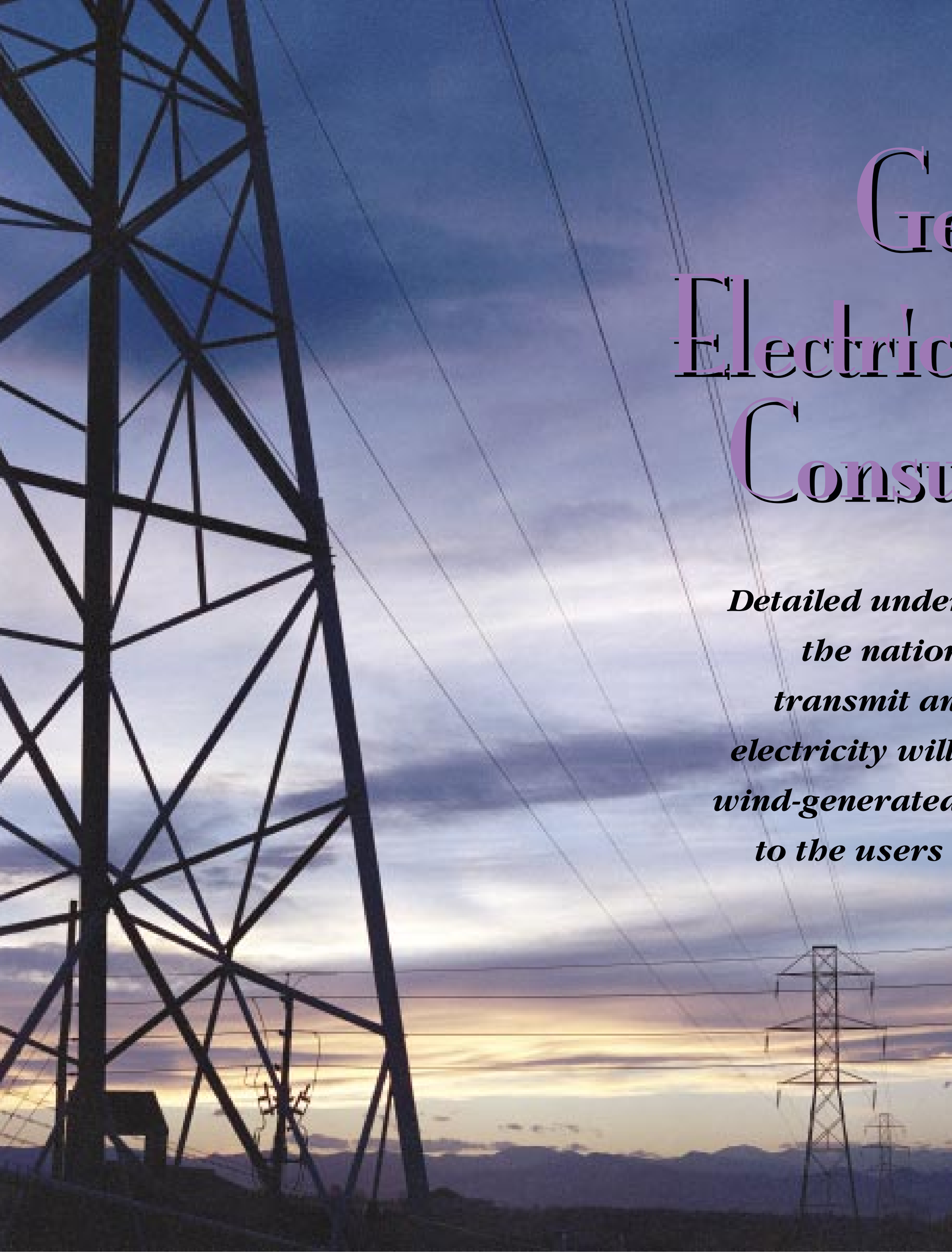


The performance of small wind turbines is being monitored under three DOE-sponsored projects: field verification, state energy, and Native American projects.

power electronics. Established in 1963 by R&D Magazine, the R&D 100 Award recognizes the 100 most technologically significant new products of the year. The competition is international and has a rigorous and formal evaluation process that includes as many as 100 independent industry experts. The North Wind 100 was recognized by R&D Magazine as one of the top three of the best 100 new products.

In 2000, a proof-of-concept turbine was installed and tested in Graniteville, Vermont, and a second prototype was delivered to the NWTC in 2001. Engineers at the NWTC and Northern Power Systems will complete analyses of the prototype turbine design and engineering documentation, and will perform certification testing of the turbine.

In addition to development projects in cooperation with manufacturers of small wind turbines, DOE, through its Golden Field Office, established the field verification project for small wind turbines in 1999 to help U.S. companies complete instrumented field testing of small wind turbines. In 2000, five agreements were under way to install 16 turbines at 13 sites having diverse conditions. Eight turbines were installed, and data were collected at host sites owned by businesses, homeowners, American Indian tribal organizations, and wind system developers. The wind-generated electricity can be used to purify water and to operate a greenhouse, a science center, a land trust, and several residences. Reports of each wind turbine's performance, operation, and maintenance characteristics help turbine manufacturers and host organizations design future products and projects. Small and large wind turbines will also be installed and monitored, beginning in 2001, under the DOE regional field verification project. ◆



Getting Electricity to Consumers

Detailed understanding of the nation's system to transmit and distribute electricity will ensure that wind-generated power gets to the users who need it.

BECAUSE LARGE AMOUNTS OF ELECTRICITY CANNOT BE STORED ECONOMICALLY, THE ability to deliver it to users as soon as it is generated is critical to effective utility operations. Utility analysts agree that the electrical transmission system in the United States is reaching its capacity. New electrical generating plants will need adequate transmission capacity, and expanding capacity can be very expensive. Limited regional transmission capacity is of particular concern for wind developments because wind power plants must be located where the wind is, whereas plants that use conventional fuels can have natural gas or coal delivered to their door and are free to locate where transmission capacity is greatest.

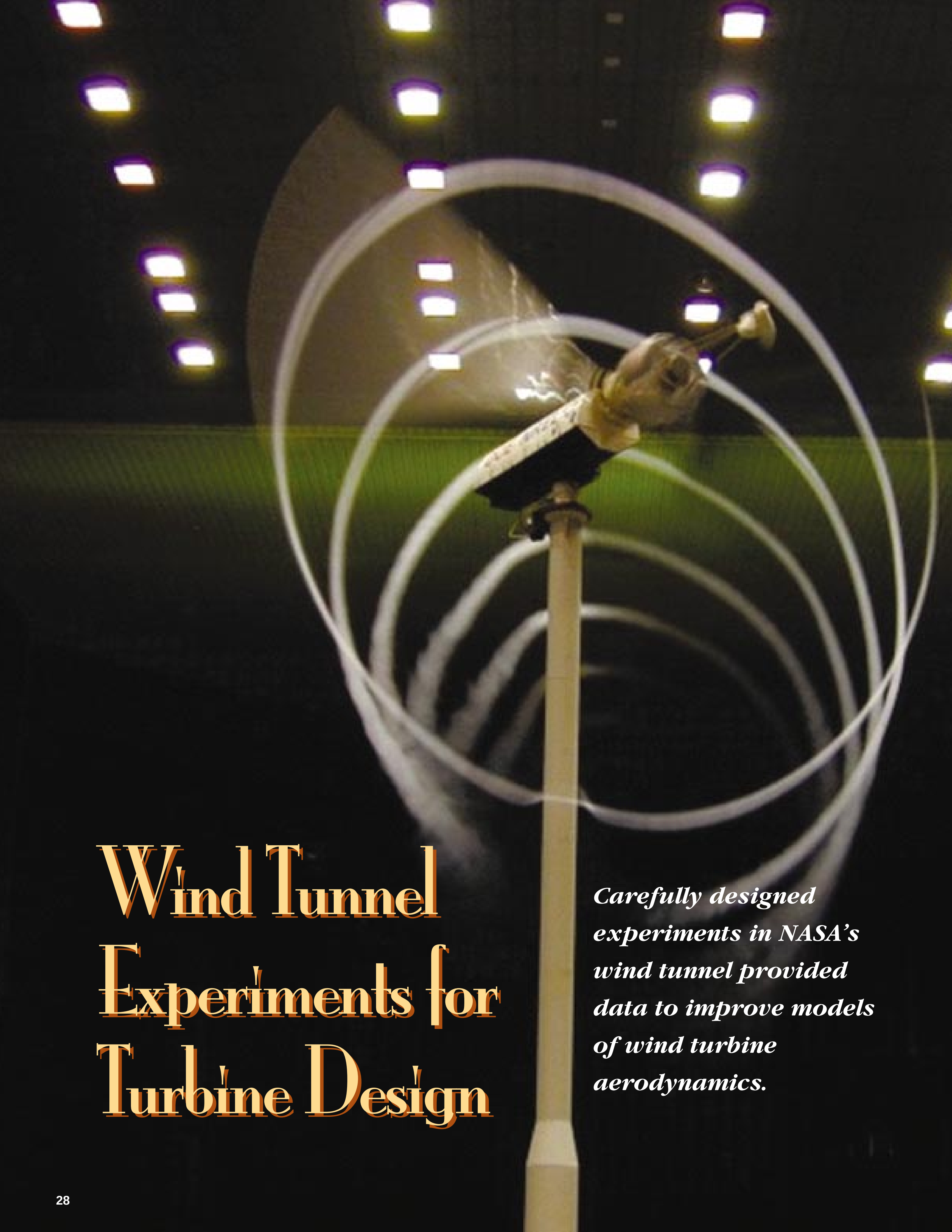
"Transmission shortage and the inability to move wind power from the source to the market is a constant, recurring theme of wind plant development everywhere in the United States," said Charles Smith, chairman of the Transmission Working Group of the National Wind Coordinating Committee. The NWCC includes representatives from electric utilities; state agencies, legislatures, and utility commissions; consumer and environmental advocacy groups; wind developers and power marketers; and federal agencies. Smith and the NWCC stress the need for a plan to address transmission issues. Transmission planning demands a better understanding of how much wind-generated electricity can be harvested and transmitted through existing power lines from the best resource areas.

Recognizing the need for better information, NREL and the Western Area Power Administration (WAPA) worked together to find out how much wind-generated electricity could be generated and delivered through transmission lines in North and South Dakota—one of the nation's richest wind resource areas. The first round of work, completed in 1999, examined seven sites in North Dakota and five in South Dakota. In this analysis, wind generation was added to each of these sites to examine the limitations of the local transmission system. Using static criteria and assumed steady-state power flow, the analysis showed that one site in North Dakota and two sites in South Dakota could integrate 150 MW of wind generation without overloading the transmission system.

Although analyzing the transmission system using static criteria can produce estimates of the total capacity in megawatts that can be transmitted across certain lines, dynamic analysis is needed for recommendations about specific wind projects. One promising region of North Dakota, the Griggs-Steele economic development zone, was selected by NREL and WAPA for dynamic analysis of the transmission lines. First they examined the thermal dynamics of the lines. Understanding thermal dynamics is critical to determining maximum transmission capacity because if too much power is transmitted through a power line, the line will heat up, expand, and eventually sag too close to the ground. Next, NREL and WAPA analysts looked at the electrical stability of the transmission system. Understanding stability is important because wide variations in electrical dynamics can interfere with transmission. At least for the Griggs-Steele area, the study concluded that hundreds of megawatts of wind-generated electricity could be transmitted over existing lines without causing problems. In addition to the specific findings of the study, researchers at NREL have perfected the dynamic analysis method for use in other regions.

NREL also worked with the NWCC Transmission Working Group in 2000 to develop a plan to address some key transmission issues. The process began at a workshop in Lakewood, Colorado, where NREL and WAPA staff, representatives from state environmental departments, power companies, regulatory agencies, and others discussed how different organizations could cooperate to solve problems of transmitting wind-generated electricity. After a lengthy process, the group reached consensus on a plan of action for the NWCC to help resolve some key transmission issues. For example, the action plan defines the role the NWCC should have in hearings of the Federal Energy Regulatory Commission to determine the rules for transmission of electricity. The plan calls for an active, coordinated effort by NWCC members in the process of developing regulations for Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs). In November 2000, the NWCC put forward a set of principles to govern operation of RTOs and ISOs. These principles were adopted through the NWCC consensus process that includes diverse interests, from power developers to environmentalists. They promote development without seeking special treatment for wind as a generation source. The transmission rules and tariffs resulting from these proceedings will have a large impact on the expanded development of wind power.

Another activity of the NWCC that could have an impact on wind energy development is using case studies of ways to resolve transmission problems. One study focused on the Upper Midwest and the Great Plains, because these regions have the greatest potential for wind development in the United States. The study highlighted the need to transport wind-generated electricity out of the Dakotas and into electrical load centers in Minneapolis and Chicago. The existing transmission systems in these areas are heavily loaded, and transmission planners are concerned about the integrity and stability of these systems. The study clarified these technical issues and identified viewpoints, benefits, concerns, and potential alliances among stakeholders in the region. This information will be used in 2001 to create a plan that will affect the entire electrical power sector in the region. Case studies are now being prepared to resolve transmission issues for other regions of the country with promising wind resources. ◆



Wind Tunnel Experiments for Turbine Design

Carefully designed experiments in NASA's wind tunnel provided data to improve models of wind turbine aerodynamics.

BASIC RESEARCH TO UNDERSTAND THE EFFECTS OF AERODYNAMICS IS CRUCIAL IN designing wind turbines that will produce lower-cost electricity. In the past, uncertainty about the true magnitude of aerodynamic stresses has prompted engineers to overdesign wind turbines—making them heavier, stronger, and more costly than necessary. Wind tunnel experiments at the NASA Ames Research Center in FY 2000 generated data that will help make aerodynamic models that more accurately predict the stresses imposed on wind turbines during operation. These improved models will allow designers to build lighter, more flexible, lower-cost machines.

The aerodynamic models used by designers today are based on simplified assumptions that are extremely difficult to test under natural atmospheric conditions. In the atmosphere, the wind flow is never smooth enough to allow engineers to separate the unsteady inflow from the dynamic response of the turbine itself. Also, the turbine response is often masked by random gusts and turbulence. One of the objectives of the NASA experiments was to measure actual turbine behavior in a controlled operating environment.

Designed to test full-sized aircraft, the NASA facility is unique. To take full advantage of this facility, researchers of the DOE Wind Program convened an international science panel to help develop the experimental protocol. The opportunity to share data from three weeks of unprecedented testing attracted close to 60 scientists from 18 organizations in Europe and the United States. The panel included experts in a wide variety of disciplines related to wind turbine aerodynamics.

After designing the experiments, science panel participants generated performance predictions in what is called a "blind comparison." They fed the technical description of the experimental turbine and the wind tunnel conditions into their own aerodynamic models. After running the models for the experiments conducted in the wind tunnel, they compiled the expected stresses on the various wind turbine components and projected the performance of the experimental turbine. The science panel met again in December 2000 to compare the actual wind tunnel results with their predicted values.

The preliminary results presented at the meeting surprised the panel participants. The first surprise was the substantial differences in predictions among the various models used by panel members. This

At left: Flow visualization tests conducted in the NASA Ames wind tunnel using smoke emitted from the tips of the turbine helped researchers determine the extent of the wake under a limited set of conditions.

The six 40-foot diameter fans in the drive section of the NASA Ames wind tunnel are powered by six 22,500-horsepower motors that use 100 MW of power.

An international science panel met at NREL's National Wind Technology Center in December to compare results of the aerodynamic experiment conducted at the NASA Ames wind tunnel with their predicted values.

was the first time such a widespread intercomparison of aerodynamic models had been performed. The second surprise was even more important. The models' predictions were significantly different from the results measured in the wind tunnel. Even simple experimental cases in which researchers had assumed the models were doing a good job showed significant deviation of the test data from predicted performance. For example, for the no-yaw, steady-state, upwind experiment configuration, the attached-flow model predictions of power output varied by 25% to 175% from measured values. Predictions of blade bending varied by 85% to 150% from wind tunnel measurements.

Researchers and model users devoted to developing aerodynamics algorithms used in these wind turbine modeling tools tend to be optimistic about the advances—especially when compared to the relatively crude capabilities available only 10 or so years ago. But the blind comparison results indicate that we still have quite a bit of work ahead of us.

The next phase of comparisons will give modelers a limited spectrum of turbine aerodynamic response measurements with which to calibrate their models. Then, using the calibrated models, participants will repeat the predictions of turbine performance calculated during the first phase.

This enormous new data set from controlled wind tunnel tests will be used in conjunction with existing data from field tests to improve and validate enhanced engineering models for designing and analyzing advanced wind energy machines.

Other activities in aerodynamic research help U.S. industry compete abroad. One example is cooperation with member countries of the International Energy Agency (IEA). Cooperation to support international databases of rotor aerodynamics and wind characteristics was supported when NREL hosted an IEA annex meeting on the international database of characteristics of field rotor aerodynamics. ◆

The test protocol at NASA

A series of key experiments were conducted by NREL scientists at the NASA Ames Laboratory, National Full-Scale Aerodynamics Complex in northern California's Silicon Valley. The tests took place in the 80 by 120 foot (24.4 m by 36.6 m) section of the open-throat wind tunnel. The facility's six 40-ft, 22,500-hp fans can produce wind velocities up to 50 meters per second (115 miles per hour). A 30-ft (10-m)-diameter, 20-kW research turbine was tested in different operating configurations. This turbine had been field-tested in various configurations since 1989 at DOE's National Wind Technology Center near Boulder, Colorado. In the wind tunnel, the turbine was always operated with two blades in a fixed-pitch control configuration at constant speed. Then the turbine was operated both upwind and downwind of the tower, with the hub in each of rigid or damped-teetered configurations. Blade pitch angles, pitch motions, and yaw positions were measured for a variety of wind speeds. More than 1700 different test conditions were run in the wind tunnel experiments. About 2,190 data sets were collected. Most sets were from tests lasting 30 seconds.

The distribution of aerodynamic forces along the airfoil was measured with pressure tap sensing devices that were calibrated every 30 minutes. Turbine structural responses were measured with instruments including blade root flap and edge strain gauges, biaxial blade tip accelerometers, teeter damper force sensors, and a hub hard-link force sensor measure-to-measure blade and hub loads. Blade pitch, blade flap angle, rotor azimuth position, and turbine yaw angle were measured with absolute position encoders. Forces inside the nacelle, the streamlined enclosure of the turbine, included measurement of low-speed shaft bending and torque with strain gages, nacelle motion with a tri-axial accelerometer, and nacelle forces with a yaw torque sensor. At the tower base, a balance system capable of measuring turbine moments and forces was used.

In addition to data collected by the turbine and tunnel instrumentation, some flow visualization was performed. The purpose was to help determine the extent of the wake under a limited set of conditions. This was accomplished by emitting smoke from the tip of one blade and videotaping the resulting helix from two angles.

The heart of the unsteady aerodynamic experiment conducted at NASA is the pressure system shown here. The system consists of 130 1-mm pressure taps and five spherical 5-hole probes that measure flow angles near the leading edge of the blade. These measurements are used to compute flow angles and aerodynamic forces that produce power and impart loads to the structure.

The DOE Wind Energy Program in Review

The NWTC's 290-acre site north of Golden, Colorado, is the focal point for wind turbine research and development in the United States

THE U.S. DEPARTMENT OF ENERGY WIND ENERGY PROGRAM IS DIRECTED BY THE OFFICE OF Wind and Geothermal Technologies under the Assistant Secretary for Energy Efficiency and Renewable Energy. The Wind Energy Program uses the unique skills that exist at NREL and Sandia National Laboratories. The NREL program, located at DOE's National Wind Technology Center near Boulder, Colorado, provides a broad range of capabilities in aerodynamics, structural testing, field testing, structural-code development, systems analysis, power system analysis, and subcontract management. The Sandia staff, based in Albuquerque, New Mexico, provides capabilities in advanced manufacturing, component reliability, aerodynamics, structural analysis, material fatigue, and control systems. Projects and tasks are often accomplished in collaboration with university and industry researchers. Both Sandia and NREL conduct in-house and contracted research as well as development and testing for DOE and for U.S. industry.

The National Wind Techology Center near Boulder, Colorado, provides a broad range of testing capabilities.

APPLIED RESEARCH

In this section of the DOE Wind Energy Program research and development (R&D) effort, researchers work to develop basic wind energy sciences and technology. This research improves the understanding of wind characteristics, atmospheric physics, wind turbine structural dynamics, rotor aerodynamics, and integration issues of the electric power system.

• Understanding the Wind

Developing wind energy in key regions of the United States and around the world demands reliable assessments, such as regional mapping of the wind resource. Global data sets maintained by the Wind Program provide the raw material for developing databases for specific regions. Sophisticated analysis techniques, in combination with an automated Geographic Information Systems (GIS)-based regional wind-mapping system developed by the program, are refined to produce high-resolution (1-km) regional-scale maps of the wind resource.

• Wind Forecasting

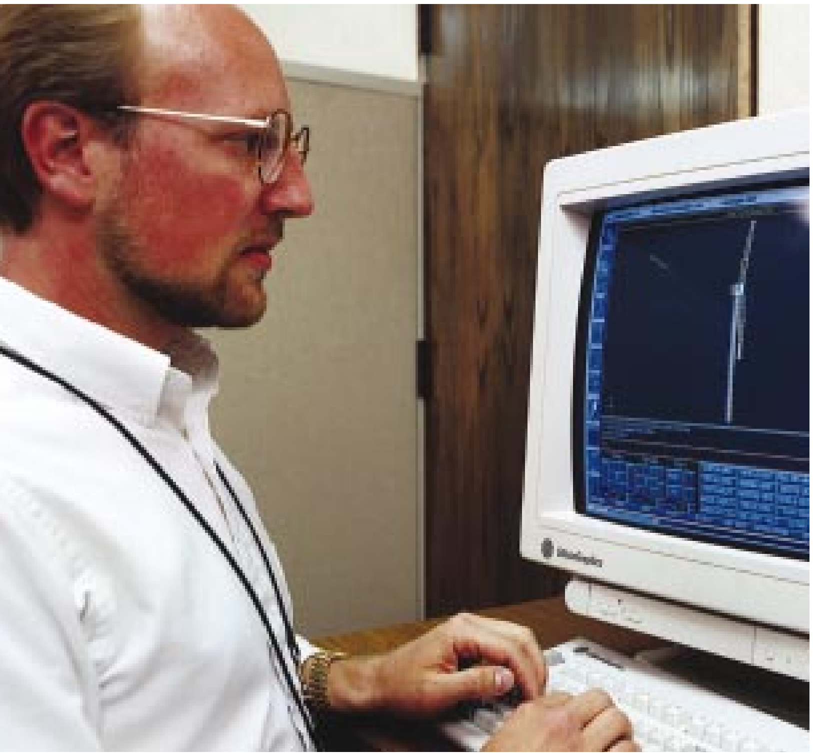
The ability to accurately predict when the wind will blow would allow wind-power-generating facilities to commit to power purchases in advance. Several forecasting models exist, and the Wind Energy Program is testing these in conjunction with active wind farms, to assess their effectiveness. Researchers at NREL and universities are also evaluating the suitability of output from numerical weather prediction models for creating new forecasting tools.

• Aerodynamics, Structures, and Design Codes

Even the most powerful computers have difficulty predicting exactly how an airfoil will perform in three dimensions that include constantly changing wind speeds and turbulence conditions. Researchers at NREL and Sandia combine two-dimensional airfoil performance data with analytic computations because this approach allows many computations to be performed quickly when evaluating a design. To improve the predictive power of these analyses, researchers are adapting a more accurate approach used for helicopter and aircraft design. They are evaluating using analyses of three-dimensional computations of fluid dynamics on the full rotor. Work is also under way to develop a special airfoil that produces little noise.

• Turbulence Characteristics and LIST Field Tests

Understanding turbulence in the wind and how it interacts with wind turbine structures is crucial to improving wind turbine reliability and performance. Researchers at NREL and Sandia have determined that no suitable data exist on the turbulent nocturnal boundary layer up to 200 m. Measurements will be taken and analyzed in 2001. Previous measurements at the NWTC and at Sandia have shown that turbulence-induced loads on wind turbines are strongly diurnal, the highest loads often being seen during the day-night transition of the boundary layer. By collecting data at higher altitudes, researchers will be able to modify and validate current codes that predict the aeroelastic and structural responses of turbines of various sizes to turbulent wind.



Computer modeling in the Industrial User Facility at the NWTC helps industry produce advanced wind turbine designs.

• Materials, Manufacturing, and Fatigue

One way to reduce the cost of energy is to improve the manufacturing process for wind turbine blades to increase their strength and reliability. Researchers test blades or sections of blades made with new manufacturing processes to verify their structural properties.

• Systems and Components

Advanced components under development at Sandia include adaptive systems that take advantage of aerodynamic forces to control power and mitigate loads by changing the shape of the airfoil. In addition, advanced control algorithms being developed will help decrease potentially damaging loads while increasing performance. To test these and other design features of wind turbines at any point in the turbine's life, researchers are developing nondestructive test methods for the wind industry.

• WindPACT

Wind Partnerships for Advanced Component Technologies is developing new technologies such as advanced flexible rotors, new drivetrains, and improved methods to manufacture, transport, and install wind turbines. The initial analyses will be completed in 2001, and the most promising concepts will be fabricated and tested in the coming years.

Wind turbine blade testing at Sandia National Laboratories helps determine mass properties.

NREL's 2.5-MW dynamometer helps wind energy researchers conduct accelerated endurance tests on wind turbine drivetrains in a laboratory environment.

• Wind Hybrid Systems

The hybrid-power test bed at the National Wind Technology Center supports industry in developing and validating innovative wind hybrid systems that incorporate wind energy, solar cells, fuel cells, and diesel or gas generators into power systems that can serve areas with small, isolated communities. The hybrid-power test bed can simulate loads and connect or disconnect storage and various generators on command. When combined with field testing and demonstration, this research gives industry the opportunity to bring new hybrid technologies to market.

• Avian Research

The Wind Energy Program conducts research to identify ways to reduce or avoid bird deaths caused by wind energy development. In cooperation with industry, environmental groups, governmental bodies, and universities, the program studies the impact of current wind plants, develops approaches to siting wind plants, and disseminates information on research to reduce or eliminate the hazard to birds.

TURBINE RESEARCH

In this section of the research program, researchers apply the new technology and design tools stemming from basic and applied research at

NREL's research in unsteady aerodynamics is leading to a better understanding of interactions between wind and wind turbines.

the National Wind Technology Center and Sandia to develop and test advanced wind turbines in various sizes to meet specific cost-of-energy goals. Wind energy can make an even greater contribution to our nation's energy supply if the cost of the electricity wind turbines generate can be reduced. The Wind Energy Program works to lower the cost of electricity through competitively awarded, cost-shared turbine development subcontracts with U.S. companies.

• Next Generation Turbine Development

Under this part of the DOE Wind Energy Program, two industry contractors are exploring new concepts and applying cutting-edge technology to the goal of developing utility-grade wind turbines. The Wind Turbine Company and Enron Wind Corporation are developing technologies that target the program's goal of producing electricity for \$0.03/kWh in areas with excellent wind resource.

• Small Wind Turbine Project

Small wind turbines for both domestic and international markets are being developed in partnership with industry. Careful design reviews, prototype tests, and preparation for certification are the hallmarks of this effort. Southwest Windpower, WindLight, and Bergey Windpower Company were participants in 2000.

• Supporting Research and Testing

The National Wind Technology Center structural test facility has been used since 1990 to test full-scale wind turbine blades for the turbine development project and for research partners in the wind industry. Engineers can perform tests for fatigue and the ultimate static strength of blades. They also perform nondestructive tests, including photoelastic stress visualization, thermographic stress visualization, and noise. A special environmental chamber can be fitted around the test apparatus to test material strength under extreme hot or cold conditions.

The center's 2.5-MW dynamometer test stand is a unique tool for improving performance and reliability of wind turbines by testing full-scale drivetrains to understand the impact of various design and manufacturing approaches to turbine configurations.

• Turbine Verification Project

The wind turbine verification project is a continuing effort of DOE, the Electric Power Research Institute, and host utilities and operators. The program has monitored performance at seven wind projects representing a range of sites, turbine designs, and operation and maintenance approaches.

The wind projects are located in Ft. Davis, Texas; Searsburg, Vermont; Glenmore, Wisconsin; Algona, Iowa; Springview, Nebraska; Kotzebue, Alaska; and Big Spring, Texas. The wind turbines in these projects include twelve 500-kW Zond Z-40A, eleven 550-kW Zond Z-40FS, five 750-kW Zond Z-50s, two 600-kW Tacke 600e, ten 66-kW AOC 15/50, forty-two 660-kW Vestas V47, and four 1.65-MW Vestas V66 turbines, respectively. Additional information on the turbine verification project, including specific information from each project, is available from EPRI at http://www.epri.com.

From remote villages in Alaska to farms in Iowa, from the passes in California to the ridges in Pennsylvania, DOE's Wind Energy Program works to keep the technology competitive and help meet the nation's growing energy demands.

• Small Turbine Field Verification Project

This project offers U.S. manufacturers opportunities to verify and publish the facts on performance and reliability of wind turbines up to 100 kW. They can also evaluate the effectiveness of their turbines in a range of distributed power applications in various regions of the United States.

COOPERATIVE RESEARCH AND TESTING

In this section of the research program, engineers work with industry to resolve near-term technical issues. This involves a wide range of work, including verification of advanced turbine performance in field tests, analysis of utility applications, participation in developing standards, and performance of certification testing. It includes all certification testing of new wind energy systems and the testing and certification of components, as well as work to advance wider use of wind turbines in commercial generation of electricity. Grants have been awarded to industry, electric utilities, and state energy offices to encourage varied uses of wind power in 10 states.

To support the goal of greatly increased contribution of wind energy to the U.S. electrical supply, DOE assembled a team of experts from NREL and Sandia to work in close coordination with the Federal Energy Management Program to gain commitments from federal facilities to purchase wind-generated electricity. They also work with state organizations to increase the number of states that have innovative pilot projects using wind energy. Working with rural development organizations and Native American tribes, the team will promote new institutional arrangements to use wind power for rural economic development. Working with the National Wind Coordinating Council and the Utility Wind Interest Group, the team will continue to support analysis of transmission constraints to developing wind power.

• Certification and Standards

The DOE Wind Energy Program continues to play a major role in developing international standards and working to ensure their application in certification testing and accreditation programs. At the request of U.S. industry, the National Wind Technology Center has become an accredited test laboratory able to supply test reports and design reviews to any certification body around the world.

• Wind Systems Integration and Value

With restructuring and technological change in the utility sector, there is increased need for independent analysis of the technical and economic aspects of integrating wind power into the electricity generation mix. Projects conducted by researchers in the Wind Energy Program and their partners in the utility and wind industries develop new information on integration issues and the reliability of new wind turbine products. ◆

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